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Digital Management Methodology for Building Production Optimization through Digital Twin and Artificial Intelligence Integration

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Abstract: In a construction project schedule, delays in delivery are one of the most important problems. Delays can be caused by several project components; however, the issue is amplified when delays occur simultaneously. Classifying delays is relevant in order to allocate responsibility to the parties. In Italy, the delay in the delivery of medium and large-sized works in residential urban centers is about 15% compared to the project forecast. Moreover, the AECO sector's ability to adapt to emerging challenges, such as environmental sustainability and digitization, is limited by the lack of innovation in management methods. The aim of this research is to create a methodology for managing the built and to-be-built environment in a digital way. This will optimize the building process by reducing delays and waste of resources. The methodology will use tools such as digital twin (DT), Building Information Modeling (BIM), Internet of Things (IoT), and Artificial Intelligence (AI) algorithms. The integration of lean construction practices can make the use of these technologies even more efficient, supporting better workflow management by using the BIM environment. The paper presents a methodology that can be applied to various scaling factors and scenarios. It is also useful for construction sites that are already in progress. As highlighted below, this brings significant economic-temporal advantages.

Keywords: building production; digital management; digital twin; BIM; IoT; AI; machine learning

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1. Introduction

Nowadays, the Architecture, Engineering, Construction, and Operations (AECO) sector is at the center of a rapid evolution driven by the necessity to align with changing needs and emerging challenges, including environmental sustainability and digitalization [1]. However, the sector's ability to adapt has been limited by a lack of innovation in management methods, which has delayed progress towards key objectives such as operational efficiency and a reduction in wasted resources. The construction industry has experienced a slower adoption of digital technologies compared to other sectors. This can be attributed to several factors [2]. Resistance to change in traditionally conservative sectors like architecture and engineering can impede the adoption of new digital technologies. The complexity of projects, with a wide range of variables and phases, can make it challenging to implement digital solutions that cover all aspects of the project lifecycle. The high investments required for the acquisition of hardware, software, and staff training are a further obstacle to the sector's digital transition. The lack of standardization and interoperability between the different software and platforms used can further complicate the adoption of digital solutions and reduce their overall effectiveness. The resistance to change and innovation within an organization can be attributed to various cultural barriers. One such barrier is a deep-rooted attachment to traditional systems and procedures [3]. In addition, strict industry rules and regulations can limit the uptake of digital solutions, especially if they are not fully integrated into existing regulatory processes.

To overcome these challenges, an integrated approach is required that actively involves stakeholders, including businesses, governments, academic institutions, and the technology industry. This will help to overcome barriers and promote greater efficiency, innovation, and sustainability in the sector [4]. The limiting factors mentioned above have significant implications throughout the work's lifecycle, from planning to disuse/reuse. In the construction phase, it is well known that delays in the finalization of construction work remain a characteristic challenge in the construction industry [5]. Comparing the possible causes of delays at the European level, it was found that when considering projects realized with traditional methodologies and projects achieved using BIM, there is a decrease in delays in favor of the use of digital methodologies [6]. Sepasgozar et al. analyzed multiple scientific papers to highlight the predominant factors causing delays in the delivery of a project in 29 different countries [7]. Elizabeth et al. presented the findings of a quantitative literature search aimed at identifying the main causes of delays in construction projects. A total of 47 articles were analyzed, revealing 1057 different causes of delay [8].

A crucial aspect of architectural and engineering projects is the delivery of activities within the agreed timeframe. As exceeding project deadlines can have serious consequences for the delivering organization, such as cost overruns and damage to corporate reputation, it is essential to distinguish between causes of delay that can be considered justified and those that cannot. Al Momani investigated the causes of delays in 130 public projects of various construction types in Jordan. The primary causes identified include design issues, changes requested by users, adverse weather conditions, site difficulties, delivery delays, economic instability, and variations in the quantity of work [9]. Assaf et al. conducted a survey on the time performance of various types of construction projects in Saudi Arabia to identify the causes of delays by interviewing owners, consultants, and contractors. The survey found that 76% of the contractors and 56% of the consultants reported an average delay of between 10% and 30% compared to the original duration [10].

Some of the most common design errors include incorrect specifications or poor communication between the various actors involved in the construction process, which can lead to material procurement and management errors. Contractual and legal errors can also have significant effects on the project timeline. The absence of clear definitions of contract terms and conditions can generate uncertainties and disputes between parties; an inadequate understanding of regulatory requirements can cause delays in the permit approval process and review stages. Financial errors such as underestimating costs or inappropriate budget control can lead to unexpected delays in project completion. The most common errors in different activities of a construction project are listed in Table 1.

To assist in visualizing the impact of errors on project delivery time, Figure 1 highlights the Relative Importance Index estimated for each process phase [11,12].

The use of new technologies opens up the globalization of the construction business, leading to a careful reflection on the potential of using BIM as a tool to approach digital management. The adoption of digital methodologies underpins the transformation process of the built environment industry. At the national level, on the other hand, the analysis carried out by the Bank of Italy provides an in-depth look at the construction phase duration of public works in Italy based on information over a period of about 15 years [8]. This analysis focuses on the internal and external dynamics and actions involved in the realization of a project by correlating different factors through specific statistical methodologies. The common quantifying factor is the time between a fixed starting point and a closing event. The focal point of this multivariate statistical model is in its application as a function of time, whereby, by comparing causes to quantities, it is possible to detect a specific time lag in the progress of work. In fact, by applying the duration estimation method, it is possible to note that, in the execution phases of projects, significant intervention is required to reduce the causes that generate delays in the delivery of the work.

Table 1. Main causes of construction delivery delays [11] by process area.

Area	Causes of Construction Delivery
Schedule	Unrealistic program schedule
Schedule	Long decision-making processes
Contract/Legal	Incorrect or incomplete contract documents
Contract/Legal	Late approval of design documents by the owner
Contract/Legal	Design and owner legal disputes
Contract/Legal	Delays in obtaining permits and acquisitions
Construction	Improper project delivery method selection
Construction	Over-ordering of changes during construction
Construction	Delays in providing and delivering the site to the contractor
Construction	Use of improper construction methods
Construction	Contractor inefficiency in work provision, equipment, materials, subcontractor management
Economic/Financial	Late payments by the owner
Economic/Financial	Financial difficulties and contractual mismanagement
Economic/Financial	Financial issues with the designer
Communication	Inadequate communication and coordination between owner, designer, and/or contractor
Communication	Confusion over work scope between owner and designer
Experience/Quality	Poor owner's quality assurance (QA) plan
Experience/Quality	Lack of owner management staff
Experience/Quality	Inadequate contractor experience, low site management, and quality control
Experience/Quality	Inadequate designer experience
Design	Design errors
Design	Project design complexity and ambiguity
Design	Delays in the provision of design documents by the designer

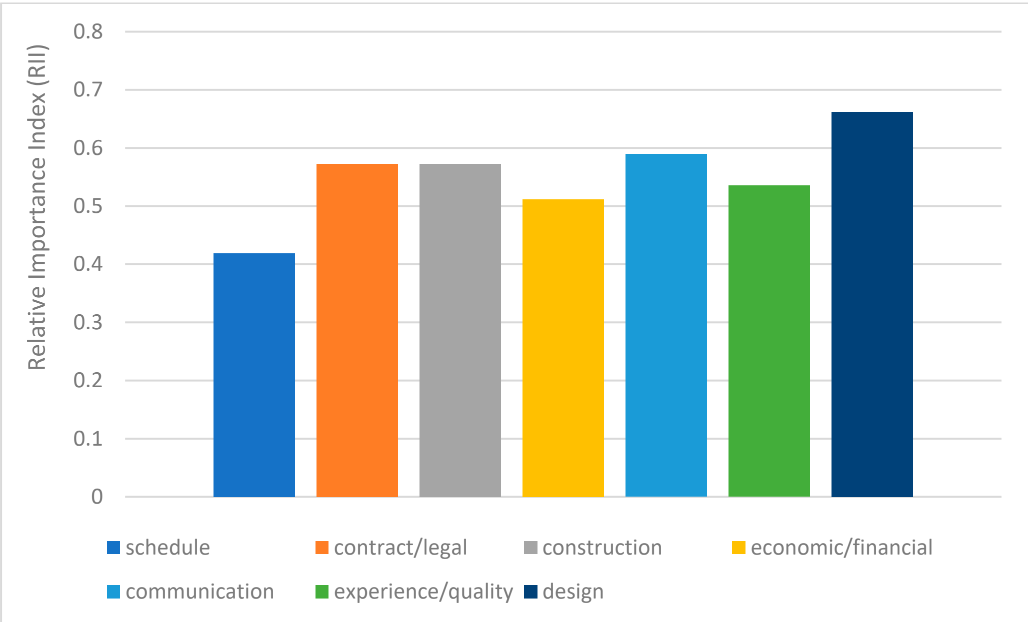


Figure 1. Delays index [12] by process area.

The duration models for the estimation of times and possible causes of delays are fed from the databases available on digitally open platforms, such as BDAP or SIMOG [13]. The proposed methodology enables digital management to foresee unexpected and possible conflict situations while avoiding the consequent project variants; at the same time, it enables the implementation of solutions that consistently avoid the waste of resources. The cornerstones for digital management are a digital model with a high level of information, connected and shared through cloud management strictly focused on achieving contractual objectives. In addition, as the works are located in large urban centers, the implementation of a digital information flow with the digital model enables the management of the typical problems of construction sites affected by a high level of car and pedestrian traffic in the surrounding area as well as the limited availability of on-site material storage. Optimization is quantified in units of time, which derives in the management section from the prediction of unforeseen events in the realization phase from the implementation of strategies conditioned by the project team through the use of AI systems capable of predicting and providing valid and immediate alternatives supporting decision making [14]. Therefore, it appears that a reduction in the delays in the delivery of work is consequential to the implementation of a digital process perpetually implemented by an information flow integrated into the BIM model. The use of IoT devices, including presence or temperature sensors, computer vision cameras, and smart actuators, enables the optimized management of time and workforce through the real-time monitoring of construction activities.

To maximize the benefits of digital twins in this area, it is essential to ensure a smooth connection and accurate prediction of data exchange between the real and virtual worlds [15]. Furthermore, the digital model is prepared to evolve over time to become a DT environment, capable of handling post-opera maintenance requests, energy management, and building automation [16–18]. The management process is automated thanks to Machine Learning (ML) systems and AI algorithms that are flexible and adaptable to the various scenarios generated by the unforeseen events encountered, as well as able to efficiently manage the entire construction process with the suggestion of precise solutions to direct the choices of the stakeholders. The adoption of digital solutions in the construction sector has the potential to foster digital transformation and innovation throughout the AECO sector and in the management of natural resources [1]. This interconnection between different disciplines in the same sector can lead to synergies and new opportunities for economic growth and technological development. It is important to consider that the optimization of construction processes through digital solutions contributes to a reduction in environmental impact; it is indeed true that reducing material waste and optimizing the energy efficiency of projects can make a significant contribution to long-term environmental sustainability, supporting necessary efforts to address the challenges of climate change and reducing the environmental impact of human activities [19,20].

This research aims to develop a comprehensive methodology for the digital management of building production in the context of the digital transition of the AECO sector, proposing a holistic approach that addresses both existing buildings and those still in the design and construction phase, covering the entire lifecycle of structures. Although there are various methods in the literature that use digital systems to optimize the construction process, these are sometimes limited or aimed at specific objectives to solve individual types of problems. The innovation of the proposal could be identified in its ability to be applied in every phase of building production, taking responsibility for processes ranging from site management to predictive maintenance, and synergistically integrating digital technologies such as BIM, DT, AI, and IoT. BIM facilitates collaboration between the various stakeholders in a project by enabling more efficient management of information and better coordination of activities; DT enables energy/architectural diagnosis of the structure and automation of the building; AI intervenes to optimize decision-making processes, analyzing large amounts of data and providing recommendations to improve efficiency and quality of work; IoT enables real-time data collection from devices and sensors distributed in buildings, allowing continuous monitoring of performance and the possibility of predictive intervention to prevent failures or inefficiencies.

The integration of the aforementioned digital technologies maximizes the efficiency of the building process, reducing downtime and wasted resources, and effectively improving the overall quality of the construction process.

2. Materials and Methods

The prolonged nature of renewal operations is a known problem and is mainly due to the use of traditional building methods. In the context of digital approaches, BIM fits into different phases in building production, improving the planning of human and material resources and enabling a regular dialogue between the actors of the various disciplines [21] (Figure 2). Liao et al. quantified the time savings, eliminating the overlapping of incompatible work on site and, consequently, excluding the possibility of having idle teams of workers (non-value-added activities) [22,23].

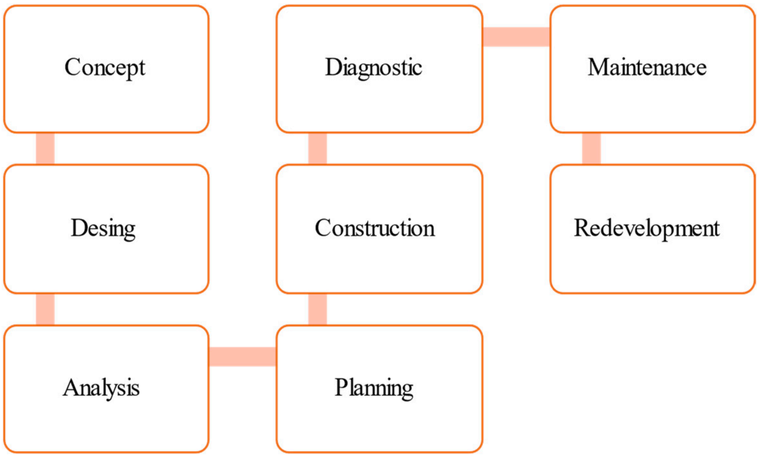


Figure 2. BIM applications in building production.

In this context, this paper aims to structure a digital management methodology (Figure 3) that is also applicable to the realization phase of work in order to reduce the delays of the end of works through BIM. The proposal seeks to meet this critical gap by highlighting a number of technologies and working methods that can mitigate the extension of the construction time in favor of higher quality and lower costs, with a significant impact on environmental, social, and economic sustainability. These factors are closely associated with construction time. In order to meet this need, it is necessary to achieve the fourth dimension through digital tools, realizing a process in which the three-dimensional models are connected to a dense network of information related to the scheduling time of the activities [24]. The creation of a 4D model makes it possible to deal with the contingencies of traditional scheduling by bringing discrete advantages, such as optimized management of design documents, upgrading site coordination, and an analysis of the impact of possible variants on the project timeline. On the other hand, the 4D BIM model requires a deep and thoughtful understanding of its functionality before the project team can utilize it. On the basis of a BIM model and large amounts of inspection data derived from Internet of Things (IoT) devices, the digital approach returns simulations that can virtually predict the execution of tasks and related cooperation between workers [25,26]. Cyber-physical systems (CPSs) are computer systems composed of physical elements with computational capacity that can interact continuously with the physical environment in which they operate, and the IoT in particular plays a leading role in the monitoring of critical infrastructures [27–29]. The Internet of Things is a cyber-physical system consisting of integrated electronic devices, software, sensors, and network connectivity, which allow these objects to collect and exchange data to contribute through Artificial Intelligence (AI) algorithms to the decision-making process. Peripheral devices operate mainly as detectors to gather information from the physical environment or as actuators to control objects.

The most commonly used detection devices are passive infrared (PIR) sensors, which measure the infrared light radiated by objects in their field of view [30]. The use of these devices makes it possible, with total respect for privacy, to monitor the coordination of the various works on site, thus avoiding critical situations that would lead to delays in the delivery of the work.

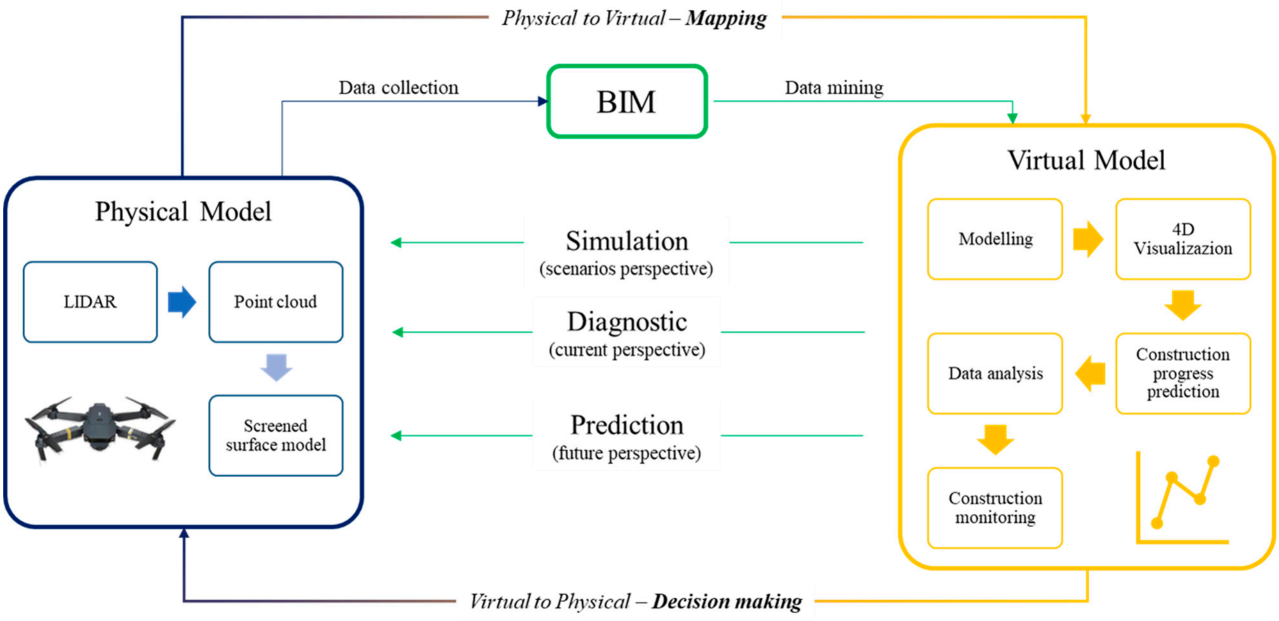


Figure 3. Digital twin—BIM integration workflow.

Esraa A. Metwally et al. focused on the importance of IoT applications in buildings and highlighted that, despite technological developments, there is still a lack of in-depth research on the adaptation and standardization of IoT applications in the architectural environment. Their study proposed a framework of criteria to develop a simplified method useful to assess the level of IoT implementation and the impact of its applications in buildings [31]. Guneet et al. implement an Elman-type recurrent neural network model and an exponential model to predict the power consumption of loads in the building environment, considering factors such as ambient temperature and space occupancy status [32]. Ling et al. highlighted the importance for companies in the AECO sector to identify digital technologies that provide them a competitive advantage during the lifecycle of an operation [33]. Sowiński et al. illustrated the use of mixed reality equipment and software to improve the safety and health of construction workers, with a focus on the implementation of ultra-wideband networking and communication technologies [34].

To date, the monitoring of safety and site activities is almost entirely entrusted to manual observation, which is laborious and extremely difficult. Jeewoong et al. integrated Bluetooth low-energy (BLE)-based location tracking technology, BIM-based site identification, and a cloud-based communication platform [35]. This system brilliantly demonstrated how the ability to detect unsafe conditions of workers in real time and analyze workers' trajectories with respect to potential safety hazards could optimize the construction process. McKinsey estimated that 50 percent of the world economy will be influenced by these new technologies to the amount of 14.6 trillion USD [36]. Digital management through the DT is a game changer for the construction industry, capable of optimizing the entire building process by combining real building data analysis with virtual model simulations [37,38]. The generated information flows constantly feed the process and provide through machine learning systems increasingly accurate solutions for the prediction of unforeseen events [39]. Pan et al. structured a closed-loop DT in the integration of BIM, IoT, and Data Mining (DM) techniques, demonstrating the possibility of anticipating possible critical situations through precise simulations [40]; by using multi-variable statistical analyses such as the Multivariate Auto-regressive Integrated Moving Average (ARIMAX) model, it is possible to organize the work and the person in detail, adapting the process to changing situations [40]. Thus, the constitution of the DT given by the integration of the BIM model and a physical cyber system combines the digital copy of the building with a constantly updating information flow.

The development of new technologies makes the building innovation process possible and aims at its improvement through digital management strategies. One of the main aspects of building process digitization is related to data management, which includes:

- cloud-based solutions for data collection, storage, and sharing;
- cloud-based processes for electronic verification and validation;
- data analysis through AI algorithms for construction progress supervision;
- implementation of blockchain technology for the management and tracking of smart contracts and agreements.

The combined use of these solutions can actively contribute to a more efficient and safer construction process, promoting the optimization of project costs and time. However, the use of these technologies may not be enough to guarantee optimization of the construction process; in fact, through integration with lean construction practices, appropriate project management of the workflow can be achieved, adequately supported by BIM tools [41,42]. Salehi et al. structured a management system based on BIM, Mixed Reality, and Lean Construction to offer opportunities to improve the quality of planning, understanding, and execution of construction projects [43]. Singh et al. exploited the potential of the BIM model as a replacement for two-dimensional designs to generate mathematical models for site layout designing [44]. Similarly, Zhang described the construction site safety situation in terms of qualitative and quantitative issues, developing through information technology a digital approach based on the teaching of technical methods with the aim of making construction site management more efficient [45]. The integration of the BIM model with CPS for training the DT through machine learning practices offers virtuous opportunities to improve the efficiency and safety of construction processes.

The use of these innovative technologies and others such as AI, cloud computing, and blockchain enable more effective management of data and processes, helping to optimize project costs and timescales. However, it is important to underline that these technologies must be integrated with lean construction practices to maximize the benefits. Adopting a holistic approach that combines technology and management methodologies can lead to significant results in the construction industry, promoting innovation and long-term sustainability.

2.1. Lean Construction Integration

The aim of the research is to develop a methodology for the digital management of building production, both for the built environment and those in the design and construction phase, covering the building lifecycle (Figure 4). The proposed methodology aims to optimize the building process through the use of tools such as DT, BIM, IoT, and AI algorithms. The integration of these digital technologies provides an opportunity to optimize processes by reducing delays and wasted resources. In particular, DT works to improve the virtual representation of structures, allowing their operation to be monitored and optimized in real time. BIM facilitates collaborative design and information management, improving coordination and communication between project stakeholders. IoT provides real-time data on building usage and performance, enabling timely intervention and preventive maintenance. Artificial intelligence algorithms analyze the collected data, identifying patterns and trends to further improve efficiency and process optimization. However, to maximize the effectiveness of these technologies, it is essential to integrate them with lean construction practices.

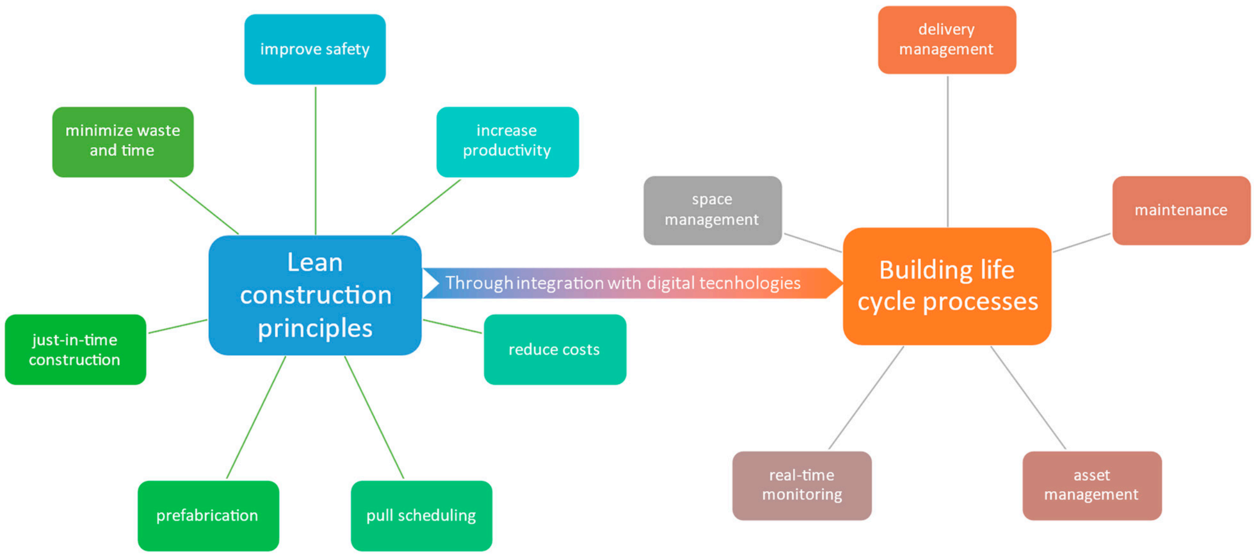


Figure 4. Key points of the building process with lean construction practices.

Lean construction principles (inspired by the principles of Lean Manufacturing) integrated with digital technologies represent a holistic approach that can contribute to optimizing the following building processes:

- Delivery Management: This methodology is predicated on the fusion of BIM and DT technologies, with the objective of enhancing delivery management in the construction sector. It proposes the utilization of AI-powered predictive models to optimize workflows and anticipate potential delays, thereby ensuring the timely delivery of projects that meet the expectations of stakeholders.
- Maintenance: The method integrates IoT and monitoring systems to establish proactive maintenance procedures, aiming to anticipate and solve any problems that occur. Through real-time data analysis, the methodology aims to prevent dysfunctions and failures, extending the building's useful life and improving its overall performance.
- Asset Management: This phase of the investigation concerns the utilization of DT and BIM for advanced asset management, with the objective of optimizing the value of assets throughout the lifespan of the building. This encompasses space management and strategic asset planning based on the 3D and 4D BIM model in order to achieve the highest possible efficiency in terms of economic, environmental, and social sustainability. The adoption of digital models using DT enables the implementation of bi-directional data flows, which facilitate the execution of remote and/or automated actions. This, in turn, minimizes energy wastage, thereby reducing greenhouse gas emissions.
- Real-time Monitoring: The model proposes the implementation of IoT sensors for real-time data collection and the Common Data Environment (CDE) on the cloud, which allows for the collection, storage, and sharing of data. The DT enables the control and execution of actions on the digital model, allowing the transmission of inputs to the physical building via the actuators. This facilitates the real-time management of the building, enabling immediate responses to change and anomalies detected.
- Space Management: The interpretation of data collected by BIM and IoT, which is enabled by artificial intelligence-based analyses, serves to enhance the efficacy of space management. Following the analysis of data pertaining to the behavior of occupants, the AI is capable of providing both routines for building automation and predictions based on historical knowledge regarding the future behavior of the building. Consequently, the facility manager is able to set the cash flow in advance, as the AI is able to forecast the energy consumption. This should result in enhanced operational efficiency and a superior user experience within the building.

The combination of the proposed methodology with the principles of efficiency and waste reduction characteristic of lean construction is proposed as an integrated architecture that capitalizes on digital technologies for optimized lifecycle management of buildings. This approach aims to lay the groundwork for future research and practical experiments to empirically validate the effectiveness of the proposed model through quantitative and qualitative analyses in different scales of building production contexts.

The lean construction methodology defines a process of constant implementation of activities by monitoring performance to achieve progressive process improvement. The identification of non-value-added activities and the continuous search for a reduction in time and economic inefficiencies must be managed through a correct and transparent exchange of information between all participants. BIM, in combination with these lean construction practices, significantly increases the chances of success in terms of results. This is possible because the digital approach allows data to be provided at the beginning of the process so that they can be available in open formats between all stakeholders involved in the construction project. The shared DT, which enables data to be collected and analyzed in real-time, makes it possible to reduce delivery delays through the elimination of non-value-added activities and through the data analysis of the process through Artificial Intelligence systems.

2.2. Digital Management Methodology

Construction process planning is the phase that organizes operational production activities by identifying time and resources. The strategy used to break down the project into basic activities is the Work Breakdown Structure (WBS), which visualizes the project components at different hierarchical levels by defining a tree diagram. However, traditional project management methods do not provide for the possibility of organizing and monitoring activities by means of a three-dimensional dynamic model. A valid solution can be interpreted through BIM-4D modeling. Through this model, it is possible to identify construction activities in a graphical manner and monitor their progress in real time, thus analyzing and preventing problems related to the spatial and temporal aspects of the project. This research study proposes a digital approach by defining a combination of the Gantt chart, WBS, and BIM model to correlate existing project management tools and digital objects, defining a digitization phase of the building process (Figure 5).

In addition, it is useful to define a set of parameters and information regarding the technical and temporal aspects of the activities with respect to the project milestones in order to carry out simulations through the model to assess the economic and temporal impacts of any unforeseen events. Therefore, the first step of the proposed methodology is the realization of a BIM model that accurately represents the real structure. In the case of a built environment, it would be appropriate to carry out laser scanner surveys to obtain point clouds as the basis for the construction of the model in order to obtain a digital replica with a high level of accuracy; in many cases, the two-dimensional drawings of the original plans do not give an accurate reflection. Alvares et al. [46] assessed the potential of using three-dimensional mapping of buildings and construction sites through images obtained via unmanned aerial systems (UAS) to support construction management activities. Gan et al. [47] proposed a method for crack detection on the underside of bridges using high-resolution images acquired using an Unmanned Aerial Vehicle (UAV) and Faster R-CNN deep learning. This approach achieved a 92.03% accuracy and a 96.54% recall rate in identifying cracks. The crack images were integrated into a Building Information Modelling (BIM) model of the bridge, enabling a more accurate assessment of its structural condition. Banfi et al. [48] have presented an integrated workflow that combines digital technologies, such as BIM, 3D cloud services, and virtual/augmented reality (AR-VR), to create high-quality immersive solutions from detailed 3D surveys. Their new SCAN-to-BIM method transfers the features of the surveyed building into a shared cloud system, supporting documentation and preservation.

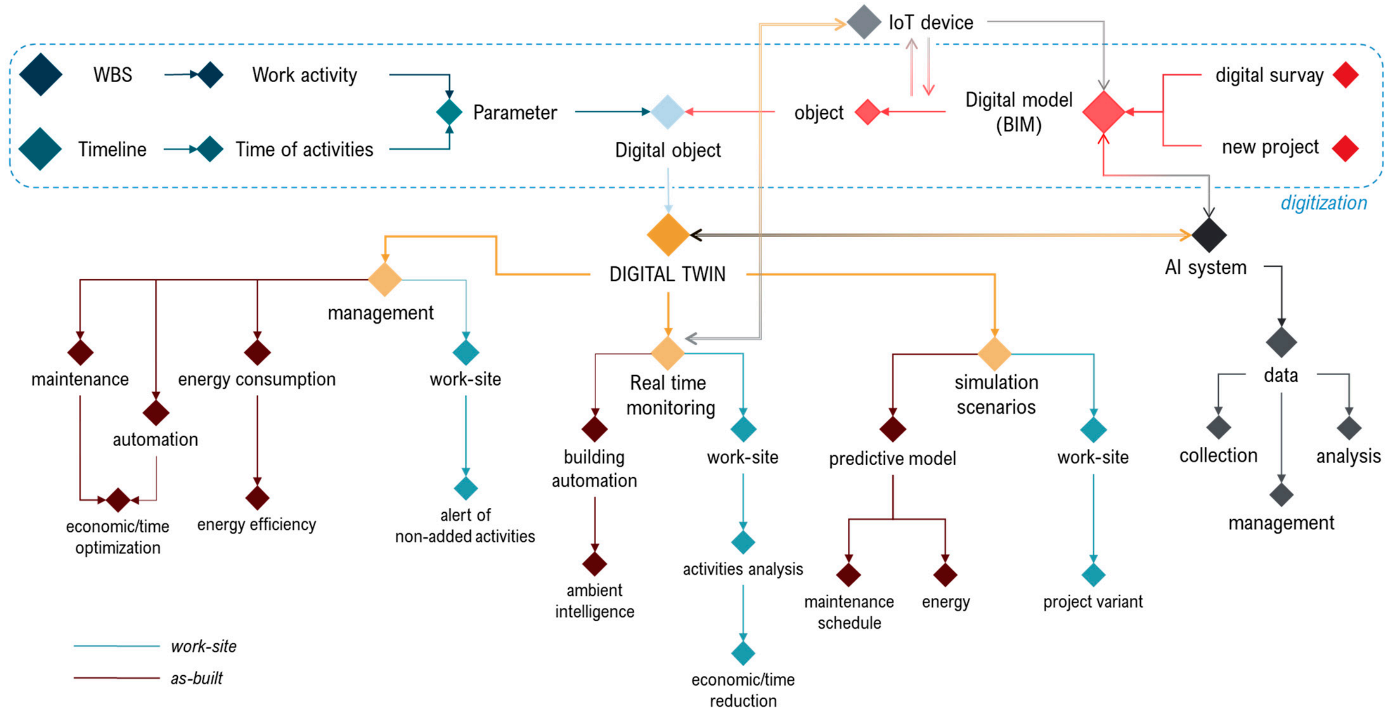
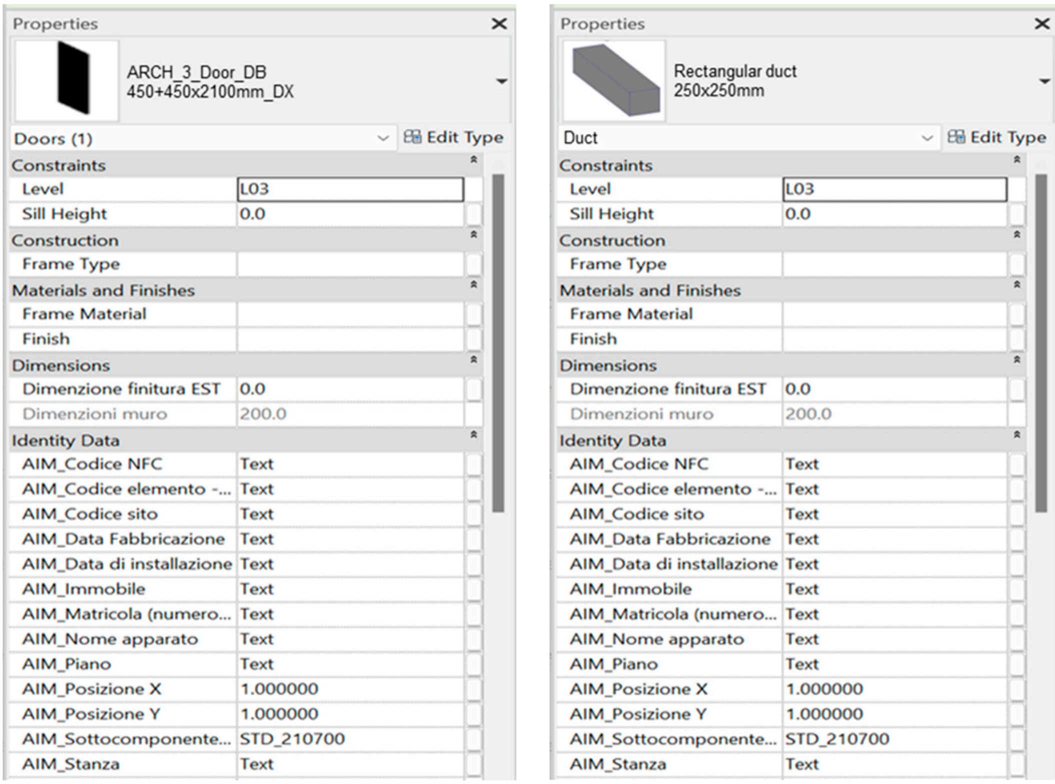


Figure 5. Design chart of the proposed digital management methodology.

At the same time, the analysis of the schedule and WBS documentation begins by applying a reverse engineering process, whereby all components are deconstructed to produce a single activity combined with the reference time frame. The data generated by this interpolation is inserted into the digital object derived from the parallel inverse engineering process applied to the BIM model. In this way, it is possible to virtually visualize for each object the activity related to it with the associated start and end dates. The parameters developed with the help of spreadsheets can connect with the BIM model using visual programming software (Dynamo for Revit 2.1). In their study, Kensek et al. [49] investigated the possibility of linking environmental sensors to a BIM model. They used various software tools, including Rhino 8, Grasshopper for Rhino, Firefly 3, Revit Architecture 2023, and Dynamo 2.1, to create virtual prototypes that could react to sensor data and alter the 3D model. Should there be any interference or unforeseen events, it is sufficient to update the data flow to synchronize the entire process, thus making the model dynamic and adaptive. At this level of progress, it is possible to analytically extrapolate the qualitative and quantitative information of the economic and time estimates to be compared with the budget curve foreseen in the planning phase and the work schedule.

By means of Business Intelligence (BI) systems, this information can be graphically employed to generate statistical data and thus compare the actual expenditure incurred in relation to the activities performed. The data can be interpolated using IoT devices, which provide a direct information flow from the construction site to the DT model that can be visualized in the properties table of the BIM environment (Figure 6). IoT devices transmit data to the CDE in .csv format. A visual programming algorithm in Dynamo is employed to insert each piece of data into the parameters of the corresponding digital element in the BIM model. On the other hand, if it is necessary to modify certain parameters manually, it is sufficient to change them in the properties menu of the element to be modified. After this operation, the IoT actuators will operate according to the new parameters entered. Once modular operations, analysis types, change requests, and analytical forecasts are established, they can be automated through AI system algorithms. Once trained with ML algorithms that capture data from user behaviors and circumstances, the AI system can be enabled to perform tasks autonomously or suggest actions to the facility manager.



(**a**) (**b**)

Figure 6. Property of digital object in BIM environment: (**a**) door, (**b**) rectangular duct.

These intelligent systems, aided by time data on previous jobs, work-site incidence data, and other datasets, provide the ability to work out solutions for the management of interference and unforeseen events that would delay the delivery of the work, besides assessing the progress of the latter. However, in the built environment, the system can interpret the data flow in the same way but for different purposes, such as maintenance, energy management, and equipment automation.

3. Results

The methodological results show that the adoption of a dynamic digital approach to the management of activities and resources on-site is an effective method to mitigate project delivery delays in the construction sector. This approach involves executing multiple activities simultaneously, enabling optimal use of available resources and preventing overlaps that could impede overall progress. This strategy allows for maximum operational efficiency, minimal downtime, and optimized allocation of labor and material resources. It also promotes flexibility in responding to unforeseen events and changes in working conditions, enabling rapid and targeted adaptation to meet emerging challenges during the construction process.

Overall, the methodology suggests a linear approach to digitizing building production, enabling the creation of a digital twin for each element at all stages of the building process. This facilitates various activities, such as building management, real-time monitoring, and scenario simulation for both the built environment and ongoing construction sites.

3.1. Digital Twin for the Built Environment

The built environment strategy was applied to an interdepartmental research center at the Sapienza University of Rome (Figure 7). The choice of IoT devices to be installed was guided by two factors: ease of installation/configuration and the availability of open software interface specifications. Following market research, devices of the type were identified:

- Shelly 2.5, a two-channel wireless relay switch that allows power consumption to be controlled and monitored separately for each channel;
- Shelly 1, wireless relay switch for home automation, suitable for switching on and off lighting points with an electrical voltage of 110–230 V, but also 12 V;
- Shelly Smart Plug S, an intelligent wireless power socket that automatically controls any connected electrical appliance;
- Schneider Electric Power Tag Link (A9XMWD20), communicating monitoring sensors with wireless technology that provide accurate real-time data on energy, current, voltage, power, and power factor. These are installed on the control panel to monitor the production of the photovoltaic system.

All of these devices have an application interface available via 802.11 (WiFi) over the TCP/IP protocol.

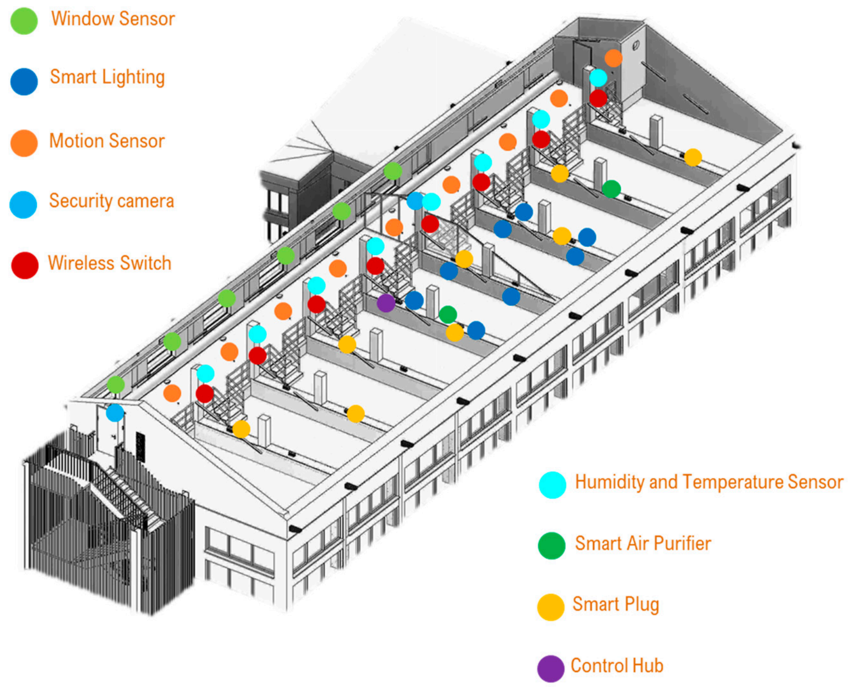


Figure 7. Digital twin model for management and automation.

All these measuring sensors were interconnected via a dedicated mixed-technology data network. This comprised cable routes (for the Schneider devices) and wireless connection components (for the Shelly devices) up to a local data concentrator (hub) connected, in turn, with a central data recording and processing system. This architecture is designed to be scalable and allows monitoring of a multitude of installations. The fundamental elements of this architecture are threefold:

- Edge: responsible for interacting with the local sensor network and acting as a buffer for automatic data and behavior;
- Proxy: responsible for interfacing with the Edge and Server, guaranteeing the connection and synchronization of data and commands (and recovery after any momentary lack of connectivity);
- Server: responsible for all computation and providing a Graphical User Interface (GUI).

The Zabbix open-source system is used to visualize and manage energy consumption and automation in medium to large environments with a large number of technological devices that consume significant amounts of electricity and lighting.

Zabbix is a control system that makes it possible to keep the detection database up to date, recording everything that happens and that has an impact on energy consumption, such as the installation of a new device or its disconnection, the movement of a device from one room to another, and its consumption measured in real time. In this way, it is possible to visually and quickly understand and control the consumption (including switching on/off) of the various devices in the rooms. It allows the capillary management of consumption, increasing efficiency and reducing electricity and heating/air conditioning costs before the consumption results are known through the receipt of the invoice issued by the relevant manager.

ML algorithms were used for the simulation of forecast scenarios. Based on the collected data, and after a training period with decision tree methods, it is possible to predict future consumption in parallel with energy production by visualizing the contents on the Zabbix system itself (Figure 8). This enables the facility manager to anticipate expenses and take appropriate action to optimize cash flow management.

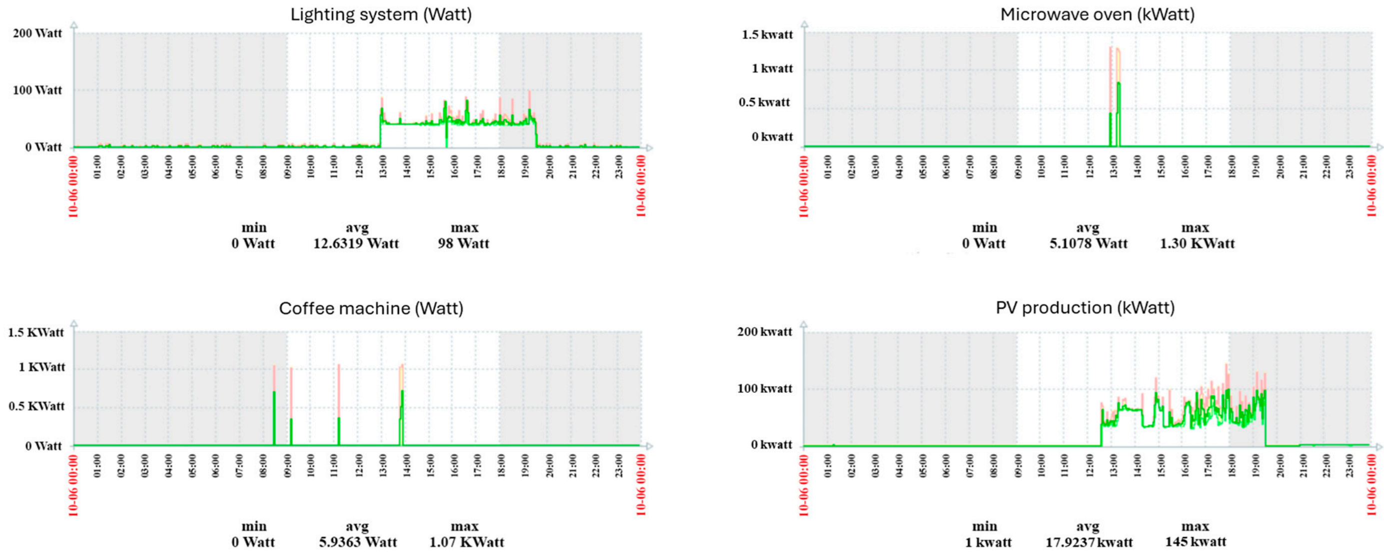


Figure 8. Zabbix system visualization: energy consumption/production forecasting scenario.

In summary, the digital twin of the built-environment model

- Building management
    - more efficient and timely maintenance, as all architectural and plant elements and their technical data sheets are available in a single parametric environment. This will result in reduced costs and an optimized lifecycle.
    - automation: it is possible to create scenarios through IoT devices to improve the quality of life or to optimize energy efficiency by using installations and lighting based on presence in the building;
    - energy consumption: by knowing the amount of energy consumed, the self-learning system is able to provide the building's energy requirements after a certain period of time, so that energy efficiency strategies can be developed.
- Real-time monitoring
    - with IoT devices, it is possible to set up an intelligent environment with building automation practices. This results in a building that can dynamically adapt to occupants' needs and environmental conditions, ensuring optimal comfort and reducing energy consumption. Thanks to automation, the building can adjust temperature, ventilation, and lighting automatically based on the presence of occupants, weather conditions, and other environmental factors, improving the quality of the indoor environment. Automation enables real-time monitoring and the management of system operations, allowing for prompt intervention in the event of faults or problems. This ensures greater safety and reliability of the building.

- Scenarios simulation
    - based on the BIM model and the analysis of large amounts of data collected over time, the DT can develop a predictive model that can simulate scenarios to optimize energy efficiency and plan maintenance and operations in advance. This enables interventions to eliminate downtime and repair costs. Through data analysis, the DT can improve the building's use of energy resources and provide recommendations to improve operational efficiency and reduce environmental impact. It dynamically adapts system settings based on expected space utilization patterns and occupant needs, providing detailed reports on building performance trends over time to enable informed decisions.

3.2. Digital Twin for the Construction Phase

The proposed digital management strategy, tested during the construction phase of a building undergoing redevelopment, is based on the creation of a digital BIM model according to the objectives of the lean construction processes discussed above. To achieve high accuracy in the digital representation of the building, point clouds from drone surveys were used for the exterior and laser scanners for the interior.

Once created, the model was georeferenced and aligned using automatic systems based on common coordinates to virtually align it with the real building. To digitize the site, a reverse engineering process was used after analyzing the time schedule and WBS, simplifying the construction phases and identifying each activity in a given time frame. The same process is applied to the BIM model so that each digital element and its relationship to the construction activities can be controlled through BI systems (Figure 9).

Figure 9. Digital construction phase monitoring in BI visualization.

At this stage, it is possible to make a precise analysis of construction progress, monitor the use of human resources, visualize cash flow trends in order to adjust the project budget, and, above all, verify that timing and quality are being met.

The accuracy of the data is dependent on the timely updating of site information. The digital model must be consistently updated via an Excel file, which is filled out at the conclusion of each activity. Dynamo allows the automatic updating of the BIM model. By applying the digitization process to all activities on the time schedule until construction is complete, future scenarios of the construction phases can be visualized (Figure 10).

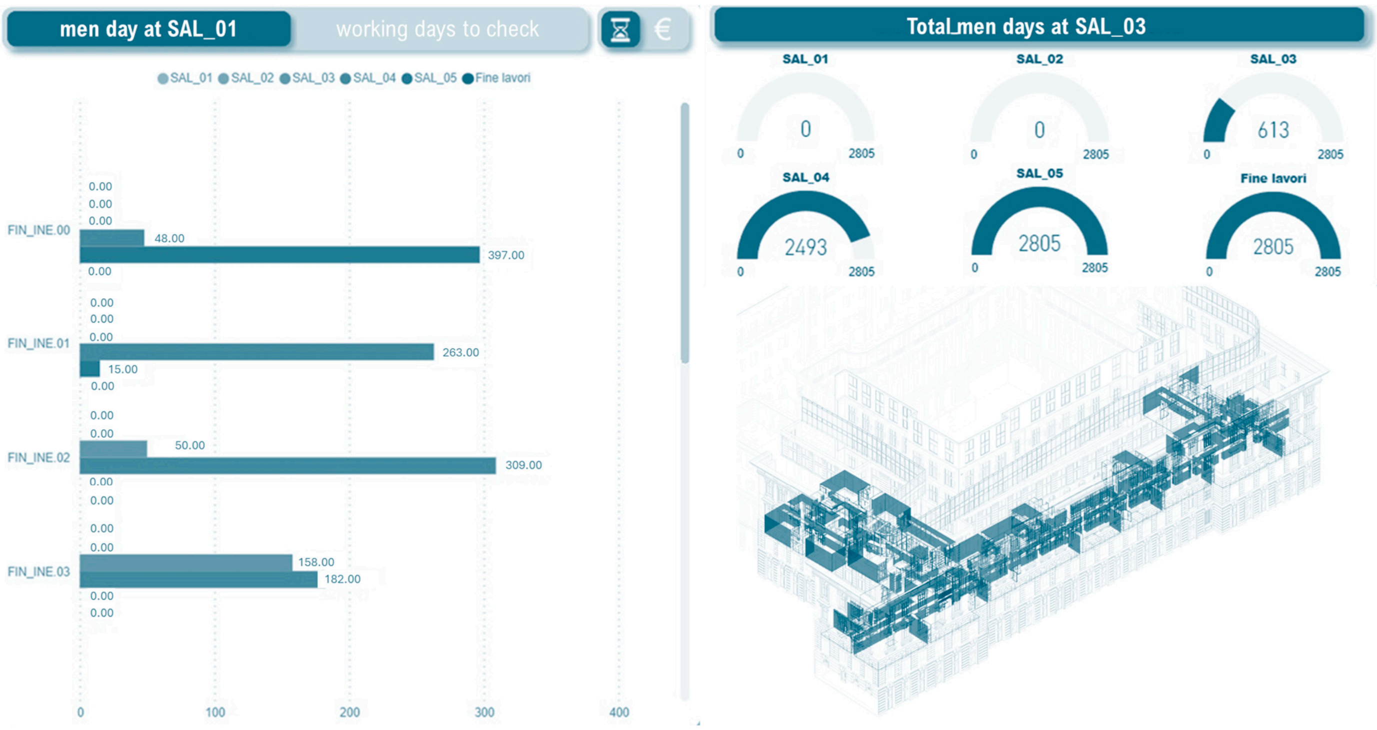


Figure 10. Simulation scenario of a future construction phase (activity: vertical wall construction).

In summary, the digital twin for the construction phase model

- Site management
    - comparing the progress of the site with that predicted using the digital model allows site resources and activities to be managed effectively. This comparison enables the identification of any discrepancies and delays with respect to the planned schedule, allowing operators to eliminate non-essential activities and optimize the process. This approach maximizes the efficiency of available resources and improves time and cost management during construction project execution.
- Real-time monitoring
    - using IoT sensors and actuators, it is possible to assess the allocation of resources in the field against the progress of activities in real-time. These devices enable the collection of data through the resources used and activities in progress, providing a clear and immediate view of the situation in the field. Information can be used to optimize resource allocation, identify inefficiencies, and take timely corrective action to ensure effective project progress.
- Scenarios simulation
    - a digital model that evolves in parallel with the actual building enables the simulation of design variants and the development of different strategies based on forecast data. This process facilitates the exploration of various design options, the assessment of their implications, and the making of informed decisions before implementing actual changes to the building. The capacity to simulate different variations and strategies aids in optimizing decision-making, reducing the risk of expensive design errors, and enabling better adaptability to emerging needs and challenges during the building process.

In both the construction phase and the built environment application, AI is used to collect, manage, and analyze data from IoT devices to interconnect a digital approach to building production. This enables combining DT model and AI algorithms with neural network streams transmitted to decision trees, aimed at supporting decision-making to manage the client's priorities.

This approach maximizes efficiency by performing multiple activities simultaneously, avoiding overlap, and optimizing the allocation of labor and resources. BIM is key in this process, providing advanced space management over traditional 2D drawings [50]. This is especially true when the BIM model is integrated with sensors, cameras, actuators, and other IoT devices that monitor access and usage of individual areas of the site in real time. To assess the effectiveness of these strategies in reducing delays, the schedule provided in the project documentation can be compared with that generated using a ML system [51]. This comparison provides a quantitative assessment of the reduction in delays and the effectiveness of the strategies implemented.

As such projects are often characterized by numerous unpredictable factors that can cause delays in delivery, a dynamic and technologically advanced approach can help to mitigate these risks and accelerate the construction process. Although the benefits may be less obvious in plant construction or dry site activities, which are often more modular and standardized, there would still be significant benefits for the client and the contractor. Greater control and more efficient management of resources can help reduce overall completion times and improve client satisfaction while ensuring greater profitability for the contractor.

4. Discussion

In the Italian context, particularly in urban centers, managing the delivery times for medium and large-scale construction projects is a significant challenge. It has been estimated that about 15% of these projects experience delays compared to their initial forecasts. This reality underscores the importance of accurately identifying the causes of such delays and clearly attributing responsibilities in order to effectively address temporal issues in the construction sector.

Additionally, according to the latest 2021 census [52], about two million buildings in Italy have exceeded a century of life. The energy improvement of these buildings becomes necessary and involves a variety of different factors, which depend on the building's history, intended use, and employed construction techniques. Therefore, the refurbishment of the built environment becomes an urgent goal, in line with European standards [53].

However, the AECO sector faces slow digitalization, hindered by resistance to change, project complexity, and high initial investments. The absence of standardized computerization further complicates the adoption of digital technologies [54].

In response to these issues, the aim of this contribution is to mitigate delays and optimize the management of the built environment through digital methodologies that can also be applied on-site. The research proposes a systematic and adaptable approach to integrate these strategies, considering both the construction and post-construction phases.

The methodology proposed in the article can be applied to various scale factors and scenarios. Furthermore, its use is also foreseen for ongoing construction sites. The application of digital management methodologies with lean construction practices allows project managers to obtain a real-time view of work progress and resource allocation.

The results of the methodological approach of the proposed digital strategy highlight that the adoption of digital systems in managing activities and resources on-site constitutes an effective method to mitigate delays in project delivery in the construction sector. This strategy, which implies the possible simultaneous execution of different activities, allows optimization in the use of available resources, avoiding overlaps that could hinder overall work progress. Through this operational mode, the adoption of BIM, IoT, and AI, can maximize workforce efficiency and minimize delivery times by optimizing the distribution of labor and material resources. In addition, it promotes greater flexibility in facing unforeseen events and variations in working conditions, allowing rapid and targeted adjustment to meet emerging challenges during the construction process.

The integration of sensors, cameras, actuators, or other IoT devices within the BIM model could provide a detailed overview of ongoing activities and available resources on the construction site [55]. For example, motion sensors can monitor access to different site areas, allowing a more efficient distribution of labor and resources. Surveillance cameras can be used to monitor the progress of work in real time and identify potential issues or delays. Actuators, in combination with the BIM model, can also be employed to activate alarm or notification systems in case of critical situations [56] or emergencies.

The use of continuously updated data for simulating predictive scenarios becomes a key analysis tool for refining planning, production, and effective resource management [57]. This helps in minimizing construction time and costs and enhances the accuracy of building performance evaluations. In summary, integrating IoT devices to enable bidirectional data exchange in the digital twin model provides innovative practices that revolutionize building management, including:

1. Resource optimization and real-time monitoring: adopting IoT in BIM allows accurate and constant control of resources, contributing to reducing delays and inefficiencies in construction projects. IoT sensors installed on construction sites can monitor various parameters in real time, such as energy and water consumption, building material usage, and the availability of construction machinery. These data, once integrated into the BIM model, provide an up-to-date view of the status of resources.
2. Workplace safety and health: air quality sensors and temperature detection devices improve working conditions, preventing health risks and ensuring safer environments. IoT sensors can detect critical parameters such as air quality, temperature, humidity, and the presence of airborne contaminants in real time. When integrated with BIM, they enable the creation of dynamic models of working environments. The system can generate automatic alarms when critical thresholds are exceeded, allowing immediate action to be taken to reduce risk. For example, if a dangerous level of carbon monoxide is detected, the system can activate automatic ventilation and notify staff of the criticality. The continuous assessment and optimization of environmental conditions on construction sites helps to reduce the incidence of occupational illnesses and accidents, improving the overall health and safety of workers.
3. Efficient management of materials and equipment: asset tracking systems contribute to better inventory management, reducing the risk of loss or theft. RFID and GPS technology can be used to monitor the location and status of materials and equipment in real time. These data, integrated with BIM, provide complete asset visibility. Analysis of tracking data enables the optimization of inventory levels, reducing costs associated with overproduction or material shortages and helping to ensure that the right materials are available at the right time. Continuous asset tracking systems help prevent theft and loss, improving site security and reducing financial losses.
4. Predictive and preventive maintenance: this technology facilitates the proactive identification and resolution of problems in infrastructures, extending their lifespan and reducing maintenance costs. IoT sensors can constantly monitor the operating condition of infrastructure, detecting signs of wear and tear or malfunctions. Using ML algorithms, it is possible to predict when a component might fail and to schedule maintenance work before critical issues occur. The collected data can be used to develop preventive maintenance programs based on the actual state of the infrastructure, rather than fixed time intervals. This approach reduces unplanned downtime and extends the useful life of assets. The implementation of predictive and preventive maintenance strategies helps reduce overall maintenance costs, improving operational efficiency and reducing the incidence of repair costs.
5. Proactive resource management: using IoT devices in the BIM model paves the way for a more intelligent and proactive approach to long-term resource management. The integration of IoT data with BIM enables more accurate strategic resource planning

based on real, up-to-date data. This enables informed decisions on resource allocations, personnel planning, and materials management. Continuous analysis of the data collected by IoT devices enables continuous optimization of resource use, adapting quickly to changes in operating conditions and project requirements. A proactive approach to resource management promotes more sustainable practices, reducing material waste, minimizing environmental impact, and promoting energy efficiency.

However, adopting these technologies is not without complications or limitations that require in-depth analysis and strategic solution development [58]. The main challenges to address include:

1. Compatibility and interoperability: ensuring that different IoT devices can effectively communicate with the BIM model is crucial. This requires standardization of communication protocols and compatibility between different technologies. The extensive variety of IoT devices, each with its own protocols and data formats, presents a significant challenge to achieving interoperability. Furthermore, the rapid evolution of IoT technologies can render existing systems obsolete or incompatible with new solutions. Effective communication between IoT devices and BIM models necessitates the adoption of standardized communication protocols and interoperable technologies. Standardization, supported by bodies such as the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC), is of fundamental importance in ensuring that data can be exchanged and interpreted correctly between different systems. The development of middleware and application programming interfaces (API) can facilitate integration, thereby improving compatibility between heterogeneous devices.
2. Data privacy and security: protecting sensitive data and maintaining privacy are critical aspects. Robust security mechanisms and data management policies are necessary to prevent unauthorized access and breaches. Cyber-attacks are becoming increasingly sophisticated, requiring more advanced security measures. It is necessary to use advanced encryption algorithms to protect data in transit and at rest, and to implement multi-factor authentication systems and role-based authorizations to control access to data and ensure that data management processes comply with data protection regulations. However, it is important to strike a balance between making data available to authorized users and protecting it from unauthorized access.
3. Technological infrastructure: developing and maintaining an adequate technological infrastructure to support IoT integration requires significant investments and careful planning. Developing and maintaining a robust technology infrastructure requires significant investment and careful planning. The adoption of technologies such as 5G, edge computing, and cloud computing can improve connectivity, processing capacity, and system scalability. However, high costs and the need to ensure long-term compatibility are major challenges that need to be carefully managed.
4. Staff training: ensuring that workers are adequately trained to use these innovative systems is fundamental for the success of the integration. Continuous training and the upskilling of staff are key points for successful IoT-BIM integration. Targeted training programs, specific certifications, and the development of digital and analytical skills are necessary to ensure that staff are able to use new technologies effectively. Overcoming resistance to change and encouraging the adoption of innovation are critical and fundamental aspects of the success of digital transformation.

After overcoming these challenges, the adoption of innovative digital systems can radically transform construction project management, leading to holistic approaches that outline new paradigms of efficiency and innovation.

Looking towards future research perspectives, the proposed methodology could incorporate additional advanced technologies (Table 2). These might include Augmented Reality (AR) and Virtual Reality (VR) to enhance visualization and collaboration in projects, robotics and automation to boost efficiency and safety on construction sites, the implementation of BIM 7D for sustainable transition, and blockchain for transparency and security in transactions.

Table 2. Impact of emerging technologies in the construction sector: innovations, safety, and project management.

Digital Technologies	Advantages and Potential	Practical Applications	Contribution to Safety and Efficiency
Augmented Reality (AR)	Enhancement of project visualization Overlaying of digital information/components onto the real world.	Virtual/digital guidance during construction phases Detailed instructions in the field of work [59].	Increase in efficiency and safety at the workplace.
Virtual Reality (VR)	Creation of virtual work environments for detailed planning and training Reduction in the risk of workplace accidents [60,61].	Staff training Exploration and planning of work in virtual environments [62].	Remote monitoring and management of high-risk activities [63].
Automation and Robotics	Automation of repetitive tasks, enhancing productivity. Reduction in human involvement in high-risk tasks [64]. Unmanned aerial vehicles (UAVs) for optimizing management practices.	Assembly of prefabricated components, demolition, site cleaning, and building maintenance [65]. Remote monitoring and progress verification of construction sites.	Improvement of site operational efficiency and safety [66].
BIM 7D	Integration of sustainability information, optimization of environmental impact, and energy efficiency of buildings [67].	Collaboration among stakeholders in the construction sector throughout the lifecycle of a building [68].	Enhancement of energy efficiency and reduction in impact.
Blockchain	Tracking and sharing of critical information Enhancement of transparency Efficiency and safety of operations.	Management of contracts, financial transactions, certifications, and other critical data [69].	Increased security and transparency in operations.

These technologies will be increasingly adopted and deeply integrated into the design, construction, and management processes of building production. This leads to more effective team collaboration, increased operational efficiency, and enhanced environmental sustainability. In particular, a user-centered approach to managing built spaces is emerging, emphasizing customization and enriching life and work experiences within buildings.

The discussion on this topic highlights the importance of an approach that synergistically combines digital technologies with advanced construction methodologies. It becomes clear that the mere use of digital tools is not in itself a guarantee of success in construction project management. It is crucial to adopt a comprehensive strategy that integrates technological aspects with organizational and social elements. The ability to adapt and modulate the methodology according to different contexts and project challenges proves essential for its effective use in a wide variety of scenarios.

5. Conclusions

The combination of appropriate behavior and conscious use of technology makes it possible to outline a precise path capable of optimizing the entire lifecycle of the building both from temporal and economic points of view [70].

The digital collaboration between BIM models and intelligent systems such as the Cyber-Physical System and Machine Learning is significantly influencing the construction industry and beyond. The proposal dealt with in detail in the paper places trust in technological development a methodology that makes it possible for the management of construction phases more efficient, upgrading time and costs. At the same time, the methodology can be applied to an existing building to set up a DT, and to monitor, manage, and analyze all components of the built environment, with the capability to simulate future scenarios or retrofitting.

The methodology was applied in two distinct case studies: one pertaining to the built environment and the other to a construction site in progress. The objective was to demonstrate the actual possibility of the different types of applications described above. The limitations of this methodology, which can also be found in other case studies, lie mainly in the limited possibility of interoperability between different software or devices. Consequently, it may be challenging to read data from different formats in a shared environment. Consequently, it is of the utmost importance at the preliminary stage to design a system architecture that is able to meet all needs and requirements at the data format level. In this perspective, when analyzing the equipment required to implement a digital management system such as the one proposed, it seems more feasible to create a homogeneous data environment for application in a built environment. The diversity of device types to be used on the construction site, which can range from drones to augmented reality viewers, via video cameras and sense-meters, makes it more challenging to create a centralized system for simplified data management.

ML systems improve as the amount of data transmitted increases and generate detailed analyses useful for decision-making. Traditional methods are static and unprepared to react promptly to unforeseen events, and these difficulties have an important economic and social impact. The effectiveness of a dynamic digital approach is enhanced by these inefficiencies and demonstrates the need to accelerate the process of technological transformation in the construction sector. By setting up dynamic digital approaches aimed at optimizing management and construction strategies, predictive maintenance models can be developed on the basis of the previously described methodology due to the amount of data connected to the digital model. The potential of the proposed system is the ability to be replicable in different situations and at different stages of the project, including the possibility of taking over in progress of a construction process with a traditional footprint.

In conclusion, a unified strategic plan for digital transition in the AECO sector appears imperative to ensure the effective implementation of digital technologies throughout the building lifecycle. Such a plan would enable the definition of common goals, standards, and procedures for the adoption and integration of digital technologies, facilitating consistency and effectiveness in building production. Maximizing the benefits of digitization, such as operational optimization, time and cost reduction, and improved environmental sustainability, can be achieved through increased collaboration among all industry players. This is crucial in addressing the complex and interdisciplinary challenges of the construction sector. Cooperation between various industries, including IT, engineering, architecture, materials production, circular economy, and environmental management, could provide the expertise and resources required to develop innovative and integrated solutions. This holistic approach would foster the sharing of best practices and the creation of synergies to promote sustainable and resilient growth in the AECO sector.

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