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Digital twinning of building construction processes. Case study: A reinforced concrete cast-in structure

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ABSTRACT

This paper summarizes the findings obtained during the development of information pipelines between a construction site and its corresponding digital twin. The case study is the construction of an office building in which independent information pipelines can track different aspects of the construction process and the aggregate result can assist managers in decision making in the form of a vaster entity: its digital twin. The digital twin prototype is designed as a recipient of information that mirror its physical building and its systems. The paper contributes with a real case in which these pipelines enable continuous monitoring and analysis of various basic parameters during construction. With a varied array of sensors installed, data was collected, organized and transmitted through a knowledge graph-based system to the digital twin dashboard. A dashboard is able to allocate many sources of data (from sensors, images or point clouds) but also, it helps visualizing data analysis that could help making informed decisions about the building during construction. The paper emphasizes the varied nature of data in construction sites as well as the importance of proper data channeling to enable multi-purpose, effective decision-making using the digital twin. Overall, the paper provides a real life insight that challenges massive implementation of digital twins within the existing construction sites for an office building. It also highlights its potential to improve productivity, resource efficiency, health and safety in construction environments. For this purpose, faced bottlenecks and challenges require refinements, more development and further research.

1. Introduction

A Digital Twin is an information construct that enables a synchronous understanding of many aspects of a physical asset by means of adequate visualization of its virtual replica. Meaningful and useful information from this physical asset can be visualized, analyzed and most importantly, used for decision-making. An active connection between the physical and the virtual realms allows the information to flow from one another at the right and expected time. Advances in digital twin technologies are considerable in other digitally advanced industries such as the aerospace, the manufacturing or the automotive sectors. Recently, digital twin technologies are called to be part of the change drivers within the construction industry as well [1,2]. In the sector, digital twins (DT) are presently defined by data representations of the physical infrastructure that absorb synchronous data from it and infuse it into the digital management processes of that infrastructural component. Data may come from many different sources. As a result, a DT is expected to include manifold different pipelines of information that enable the information flow from data-gathering to decision-making.

Advances in Building Construction, which encompasses many fields, are called to bring new economic and technological ecosystems. This may have profound consequences for both existing and new stakeholders. Industrial fabrication, digital technologies and cyber-physical systems represent three vast domains for potential growth. Digitalization of procedures within construction sites is a great challenge due to the number of non-digitalized processes and the number and variety of stakeholders. It is recognized that adop-

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tion of many of the advances found in the construction sector is presently uneven in most of construction sites. Likewise, the flow of data depends on many factor such the nature of the owner (private, public), the relationships between construction players (contractors, subcontractors, managers) and the role of companies within the site (design, construction, control, management). Building construction firms have often been identified as slow in digital adoption. Information still flows using crafted spreadsheets, A3 drawings, and clipboards even when managing large construction projects. Recognizably, long time-spans and time schedules in building construction (from months to years) do not provide an accelerated pace or accelerated needs for rapid and up-to-date technological adoption.

Building construction sites are complex and dynamic. Sequential phases such as ground preparation, construction of the structure and floors, deployment of all MEP installations, façades, HVAC or closures, imply a variety of tasks and schedules. For instance, during the erection of the structure, one may identify some tasks such as concrete casting of columns, shoring slabs, formworks for beams, etc. During the installation of façades, windows or doors, the related tasks include bespoke logistics of the installation of these systems. Digitalizing all these processes and feeding them with data from the site is often a unique tailor-made development. Tasks associated with the structural components use and require different types of information than those tasks associated with HVAC systems. As a result, a pipeline of information from one specific task to a useful DT must include and address the singularities and the stakeholders of that task. Recognizably, these pipelines still need opening many information valves by many stakeholders such as designers, construction managers, contractors, subcontractors, and owners. HVAC, MEP. The structural layer is only one of the active domains in which information pipelines can be developed.

In Building Construction, the improvement of processes is the ultimate goal. Using DT for this goal represents the challenge. For investors and decision makers, however, key aspects are needed for embracing this vision. Namely, the level of technology readiness, its ease of implementation, its usefulness and its impact are of the utmost importance. Technology readiness is desired for potential technology adoption as in other industries but, to achieve technology readiness, research is needed. Pilot cases are becoming a key ground for research in the field of DT in Building Construction. Yet, research developing DT in building construction including an active participation of many stakeholders is still at early stages. Relevant literature is presently dominated by conceptual designs and frameworks for DT in the sector [3–10]. There is a clear need of evidence based on pilot cases in which the results are gathered with an active involvement of most of the stakeholders.

This paper presents a case study of the digital twinning of an office building during the construction phase. The asset is located in the city of Barcelona, Spain at Poblenou, an extensive neighborhood that borders the Mediterranean Sea. The building represents one pilot case for the development of pipelines of information between a real construction process and its corresponding virtual counterpart. The demo case belongs to a vaster study developed within the frame of the H2020 European project ASHVIN [11] (Assistants for Healthy, Safe, and Productive Virtual Construction Design, Operation & Maintenance using Digital Twins). The purpose is to pull the digital threads and methodologies into coherent solutions to be implemented over the construction process, as well as wrapped up data systematically for further use during the life-cycle of the asset. The overall objective of the project encompasses the development of a digital twin platform and a set of applications and methods. Very importantly, key takeaways are found on the basis of gathered experiences from a total of ten demo cases including design, construction and maintenance phases. The active development of the platform also allowed researchers for the identification of challenges and technical requirements for the realistic automation of information pipelines for those ten infrastructure systems. The case study presented herein belongs to that suite of demonstrators.

The rest of the paper is organized in sections. Section 2 presents academic background for DT in Building Construction with a particular focus on pilot cases. Section 3 provides an overview of the research project and a general overview of the demo case. Section 4 depicts the construction schedule of the building as well as the time location of the developed information pipelines within this schedule. Finally, Section 5 provides descriptions of the deployed developments and Section 6 provides discussion and analysis of the challenges and requirements from different stakeholder perspectives. Finally, general yet concise conclusions are provided in section 7.

2. Related work

Following the literature in recent years, research and development (R&D) in digital twins within the Building Construction sector, one can identify two foci: (i) Conceptual designs and frameworks and (ii) Development of semi-automated pipelines of information fully or partially embedded into DT systems. This literature review focus on identifying how researchers have studied the latter. For the former, the reader is referred to Refs. [1–10], which are only mentioned succinctly.

For instance, drawing inspiration from the manufacturing sector [1] presented detailed literature knowledge from DT in manufacturing with meaningful interpretation that can be translated and applied through DT conceptual and process models for the Architecture, Engineering, Construction, and Operations (AECO) industry. From the construction perspective, investigations by Refs. [2,3] summarize the extensive literature review about the DT application in the construction industry that can be used as a basis to develop conceptual designs and frameworks. Additionally, frameworks from the operation & maintenance phase can be integrated into the building construction. Researchers in Ref. [4] developed a DT framework for facility management to guide the stakeholders make more informed decisions for their activities and generate more efficient outcomes from their assets. Likewise [5], developed a DT framework for structural health monitoring by characterizing the DT framework for simulation, learning and management.

Focusing on construction in recent years, researchers have developed DT frameworks to support the overall construction process. To develop a semantic construction DT [6] presented a framework to use multi-faceted BIM applications along with IoT and artificial intelligence to evolve towards the construction digital twins in evolutionary phases. With a similar aim, researchers in Refs. [7,8] developed a step-by-step DT workflow for the built environment aligned with the current DT state-of-the-art and support the relevant stakeholders with the best decision-making. With a focus on digital twin-based construction management [9], established a data-driven DT framework integrating BIM, IoT, and data mining to avoid potential bottlenecks and prevent possible failure for advanced project management. Likewise, to contribute to the voids of construction site logistics [10], presented a lightweight DT for transforming bulk material silos into smart silos and supporting the construction supply chain. Many actions on the development of conceptual frameworks for design, construction and maintenance of infrastructure systems are being developed in Ref. [11], the research project in which this study is framed.

On the other hand, the focus of this literature review is on examples and applications of DT frameworks construction sites. Most of those examples are relatively recent and many of them are conceived for the operation and maintenance phase. Recognizably, the construction sector is still at the phase of early and uneven integration of digitalization of processes during the construction phase. Nevertheless, many applications aimed at improving key aspects during construction are published in the relevant literature [12–24]. Enhancing productivity, safety, resource and quality are major objectives for the construction sector stakeholders.

One application of DT that attracts considerable interest is quality control (QC). Tran et al. [12] proposed an application for automatic geometric quality evaluation of As-Built prefabricated façade systems using a comparison between a three-dimensional as-designed model and a three-dimensional as-built model. An early version of pipeline is presented. Data from measurements (Point Clouds) are used for subsequent assessment of the quality. Both extremes of the pipeline are developed. Integration of BIM models are suggested as future work. Xie et al. [13] developed construction monitoring applications to track settlements during tunnel boring. Timely information related to potential disturbance of the construction surroundings was key for timely decision-making. Posada et al. [14] established preliminary information pipelines with the aim of embedding advanced inelastic structural models for sequential construction. The material properties of the structural components are tracked and included in DT for optimizing construction sequences in building construction.

Another application is Construction Safety (CS). Construction safety early warning is goal that could also benefit from comprehensively deployed DT-based management. Researchers in Ref. [15] developed and tested a DT platform that provides services and functions for tunnel construction monitoring. Several safety-related topics for workers such as air quality, machine positioning or comfort are tracked, analyzed and displayed in corresponding dashboards. One application for CS is presented in Ref. [16]. Based on deep learning techniques embedded in DT dashboards, construction sites are scanned for the sake of identifying potential wind-borne debris (PWD) able to jeopardize surrounding during hurricane events. Other research focus on integration of DT, computer vision in existing facilities and mixed reality applications as a way of improving construction safety [17]. BIM-enabled semantic webs for safety checks are proposed in Ref. [18] with specific applications on subway construction and with a considerable potential of implementation in vaster information constructs.

Productivity and performance (PP) are also key targets addressed in the literature. For instance, with the aim of monitoring logistics and transportation, an integrated BIM-GIS-IOT information construct is presented in Ref. [19] for enhancing the performance of logistics in modular construction. Applications on safe and productive construction dredger operations with particular focus on the design of DT applications for sensor monitoring and development have been presented in Ref. [20]. Likewise, authors in Ref. [21], based on virtual hypothetical scenarios integrating sensors, BIM and dashboards, provide playgrounds for assessing productivity and performance during construction. Progress monitoring, what-if analytics and compliance orders are some of the indicators used for assessing the proposed digital flow of information. Considering a tunnel scene in China as an example, in Ref. [22] a demonstrative application of tunnel digital twin construction and operations management based on 3D video fusion. An analysis of the effect of the application is also presented. Demonstrating capabilities of robotic construction and crane monitoring are presented in scale reduced 3D printed modules as demonstrators in Ref. [23]. Authors emphasized on the enabling potential of a digital twin for testing different "what-if" scenarios (i.e., to anticipate the effect of a process given a predefined situation) in robotic construction.

Table 1 summarizes the identification of key information valves on the corresponding semi-automated pipelines. Measurements, interoperability, simulation and decision-making processes are highlighted for the referenced cases. The table is organized according to different key performance indicators (KPI) such as Construction Safety (CS), Quality Control (QC) or Productivity and Performance (PP).

From the studied cases, one can conclude.

- Semi-automated pipelines of information in construction sites have been implemented rather recently. All cases are developed within the last five years.
- Not all case studies provide full integration between measurement, 3D modeling and simulation. Often, assessment is based on some of the tools but not necessarily on a timely integration of physical observations and virtual predictions synchronously.
- Most of the cases provide an assessment according to predefined KPIs.

When it comes to robotics in construction, it is worth pointing out recent research that has primarily concentrated on simulating robotic construction tasks, particularly emphasizing strategic models for factory-based pre-fabrication. Notable studies [25–27] developed frameworks connecting robotic production planning tools with building information modeling standards to simulate pre-fabrication activities. Additionally, timber frames pre-fabrication simulations have been presented in Ref. [28]. Fewer researchers have explored on-site robotics simulation, emphasizing interfaces between building information models and robotic operation systems (ROS). Specific tasks were studied, such as indoor painting by Ref. [29], masonry by Ref. [30], and excavating activities by Ref. [31]. [32] proposed a more comprehensive approach by linking the Universal Robotic Description Format (URDF) with the BIM standard IFC for on-site robotic planning.

In addition, also related to the topic, existing research analyzed off-site production of prefabricated components as controlled conditions are ensured in a factory [33]. Site observations to analyze ongoing precast production processes were deployed. Genetic algorithms utilized the gathered information to select the near-optimal schedule regarding conflicting goals of on-time delivery and the

Table 1
Identification of pipelines and applications of DT in construction sites from the literature
CS: Construction Safety, QC: Quality control, PP: Productivity and performance.

Ref. Year	Construction site	Measurements	BIM Interoperability	Simulation	Application	Assessment
[12] 2021	Prefabricated façade of a mid-rise student accommodation building	TLS point cloud. (Faro Focus 3D S120)	Not integrated	Not integrated	QC-Quantitative comparison between the 3D as-built model and the 3D as-designed model	Visual quality assessment to enable localization of construction errors. (*Productivity & Cost)*
[13] 2021	Nanning metro line 1 crossing beneath Nanning Railway Station	Hydrostatic leveling system (HLS)	Not integrated	3D FEM for comparison purposes (not integrated)	QC- Real-time platform with monitoring data and information flow for coordinated management during tunnel construction	Validated on the Nanning metro line for a settlement control goal of a maximum value of −4 mm. (*Safety & Productivity*)
[14] 2022	Office building in Barcelona (Spain)	Temperature sensors	IFC integration	Nonlinear inelastic model with rheology	QC- Monitoring of concrete formwork striking and tendons stressing	Pipeline enables a decision making and QC system based on realistic analysis. (*Productivity*)
[15] 2023	Dongtianshan tunnel construction in Hami, Xinjiang (China)	Safety, environmental, construction & auxiliary sensors and cameras	Not integrated	Not integrated	*CS*- Digital-twin based early information and safety management platform	Validated for Dongtinshan tunnel by successfully predicting a collapse accident of tunnel excavation face. (*Safety)*
[16] 2022	Residential construction sites in College Station, Texas (USA)	3D point cloud	Not integrated	Not integrated	*CS*- Identification of potential wind-borne debris for construction sites during hurricanes	The proposed method generates site-specific heatmaps respective to intensity of wind events to enable risk-informed decision making. (*Safety)*
[17] 2022	Building 8 at RMIT University campus in Australia	Imagery (vision-based tracking)	BIM integrated to extract construction schedules and building geometry information from the BIM files to generate virtual construction sites	Not integrated	*CS*- Visual monitoring system combining safety management scenarios and MR to deliver and visualize hazard information to onsite workers	Results show the system performs well in merging virtual objects with the real-world. The hazard identification accuracy is more than 96.1 %, and the average hazardous area presentation accuracy is 11.47 cm (*Safety)*
[18] 2022	Subway construction (Case study)	Axial force meters, water gauges level, clinometers	Definition of an interoperable BIM-semantic web for safety checks	Not integrated	*CS*- Automated safety checking through SPARQL-based reasoning for subway construction	Verification through a real subway construction project shows compared to a manual process the proposed method improves the accuracy and efficiency of safety checking. (*Safety)*
[19] 2021	6-story apartment modular construction (Cubix Othello, Seattle)	GPS	BIM-GIS integration	Real-time logistics simulation	PP- Digital twin framework for real-time logistics simulation to predict logistic risks and accurate module delivery time	Results indicate that the DT framework predicted an accurate ETA for logistic delivery and reduced a total of 157.5 h in idle time loss. (*Productivity & Cost)*
[20] 2021	Tianjin Port 300, 000-tin waterway phase 2 project	Physical and virtual sensors of machinery (up to 792 measurements)	Not integrated	Not integrated	*CS*- Digital twin driven virtual sensor (DTDVS) for construction safety of trailing suction hopper dredger	The DTDVS was shown to be more stable, environmentally friendly and efficient in enabling the safety of dredging operations. (*Safety)*
[21] 2022	Hypothetical construction site	Hypothetical sensor data	Not integrated	Virtual simulation environment based on deep reinforcement learning (DRL)	PP- Digital twin driven DRL learning method for adaptive task allocation in robotic construction environments	DRL's control resulted in 36 % construction time decrease compared to the rule-based model in robotic construction. (*Productivity & Cost)*

(*continued on next page*)

Table 1 (*continued*)

Ref. Year	Construction site	Measurements	BIM Interoperability	Simulation	Application	Assessment
[22] 2021	Tunnel in China	Multi-source IoT sensors	BIM used for the parametric of the tunnel infrastructure	Not integrated	PP- Digital twin creation for tunnel traffic & accident management, facility management and emergency response	The results show that the tunnel DT system based on 3D video fusion solved fragmentation and provided tool support for 2D and 3D linkage response of emergencies. *(Productivity)*
[23] 2022	3D Printed reduced scale	Cranes, robotic arms are sensored with UWB & RFID tags and industrial wearables.	BIM models used for encapsulated data to import as MiC instances	Not integrated	PP- DT-enabled smart modular integrated construction (MiC) system for on-site assembly	DT-SMiCS improved the defined KPIs such as emergency detection time and progress supervision. *(Productivity)*

minimization of production costs under resource constraints. Other researchers used historical data to compare a baseline as-is model and different lean construction principles into a simulation model for assessing modular construction options both off-site and on-site [34]. The outputs were evaluated regarding duration, efficiency, and productivity.

So far, fewer researchers focused on continuous construction progress monitoring of on-site processes. For example [35], developed a framework and workflows for the implementation of many different data sources by using the IoT for real-time decision-making in a hypothetical earthmoving operation. Another perspective is given in Ref. [36], where they applied a feature augmentation technique to limited kinematic datasets from three case studies of equipment operations. The augmentation enables accurate and generalized activity recognition. In the same field [37]. collected kinematic process data during earthmoving operations to apply process mining every two days to continuously update a simulation model and provide more reliable forecasts. Concerning analysis of equipment [38], proposed a 3D CNN-based model for real-time action detection in video recordings of construction machinery. After training on 520 clips, the one-stage model worked successfully for real-time action detection in a test of 260 clips recorded on various construction sites. Using other data sources like audio [39] proposed a method to detect construction progress by analysis of synthetic and real-world equipment audio data (e.g. loader and truck). Methods including point cloud gathering sequentially are also found in Ref. [40], where researchers proposed a method for real-time update of an as-built model by point clouds to compare the as-built with the as-designed BIM model. Further information is provided by reviews, e.g., in Ref. [41] for automated activity recognition of workers and equipment or in Ref. [42] for vision-based interior construction progress monitoring.

3. Development of a digital twin of an office building under construction

a. Motivation

This research is performed within the frame of the H2020 European project Ashvin [11], related to research and innovation actions on the development of Digital Twins as assistants for Design, Construction and Maintenance of infrastructure systems. The project covers the whole process from a vast perspective. From DT conceptual frameworks to specific tools using advanced informatics, several pipelines of information are under development. Demonstrative case studies covering buildings, bridges, footbridges or industrial buildings (airports, ports, stadiums) represent a set of test beds for implementation and development of these DT. Descriptive reports on the nature of these demonstrators are already available in Ref. [24]. This variety represents a wide perspective for grasping as many twinning possibilities as possible, which enriches the point of view as well as the definition of DT in this project.

The construction phase has both prequels and sequels. As a result, the development of DT should include both potential advanced virtual models developed at design stages and in addition, it should prepare the virtual asset for the operation/maintenance stages as well. The developed platforms and tools include these aspects as well. The information pipelines under development are thus conceived with back and forward information and knowledge flow through all stages of the asset development process. A user-interface in form of a dashboard together with an expandable toolkit enable the demonstration of the technical aspects needed. Data generated during the process of building design, building construction, and building maintenance can be collected and embedded in the same common data environment. This data is analyzed at the right time transformed to measurable performance indicators with a right-time monitoring of these indicators.

b. The Democase

In this paper, the case study is a RC building located in the Barcelona district of Poble Nou. Currently, there are considerable constructions projects under development inside this district under the umbrella of the 22@ innovation district. BIS structures, a Barcelona-based structural engineering office, together with many other stakeholders, agreed upon collaborating with Ashvin by facilitating access to MILE – a Business Campus project construction site. MILE is an office buildings project of 38.093m2, divided into three complexes: MILE Badajoz, MILE Llull, and MILE Ávila. The access was provided for the specific module, a cast-in-place reinforced concrete building of long-spanned post-tensioned slabs, consisting of eight levels, and a total area of 16.524m2. Fig. 1 shows a render and a picture of the finalized building. Fig. 2 shows the geometrical model of the concrete structure. Access to MILE was granted for the study within the premises of a specific module of the building (highlighted in Fig. 2) during the erection of the concrete frame (approximately 6 months).

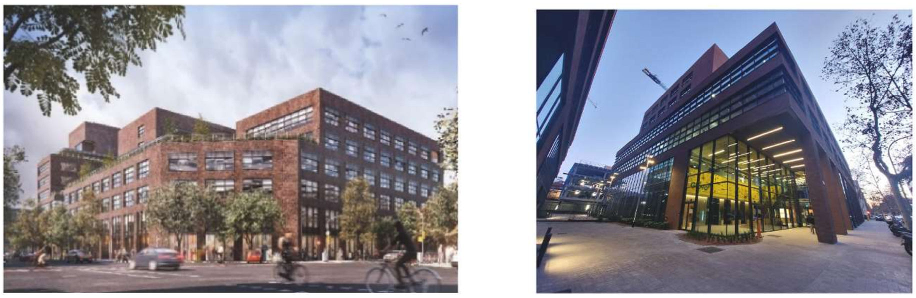


Fig. 1. Office building render a) Render provided by BIS structures b) Finished building.

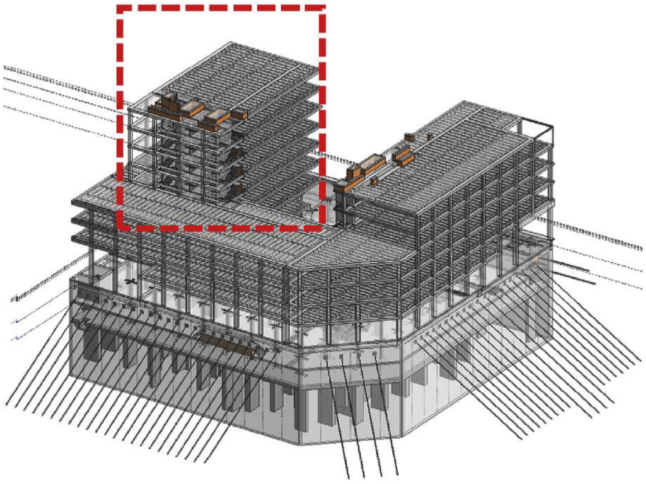


Fig. 2. Accessed module of the RC structure.

The geometrical model of the structure includes an IFC depiction of the structure. Elements are identifiable based upon IFC classes. Overall, the description of IFC classes provides a structured and standardized way to represent building information, fostering interoperability and data exchange between stakeholders. For instance, the same description of a beam can be retrieved accordingly by those interested in structural analysis of such beam or those interested in its quality control during material casting. It is worth pointing out that these IFC classes are the building blocks of the IFC schema, representing various building components and attributes. Each IFC class corresponds to a specific type of object or entity within a building model. These classes are described using a consistent and structured format. Many other codes refer to those IFC elements downstream. Visualization of results is also based upon this schema.

This case study provided a specific scenario: the construction of an in situ casted concrete frame with walls, columns, beams and post-tensioned slabs. Many stakeholders working simultaneously on this project represented an interesting boundary condition that influenced the development of the information pipelines. All pipelines of information were conceived after stakeholders defined both the scope of the access to the site, the time constraints and the corresponding approval for data-collection. The premise for data-collection was that the schedule could not be altered for reasons associated with this action. After filtering other logistics-wise unfeasible pipelines, several construction tasks were identified as sources of information.

- The concrete casting of the studied module was repetitive and sequential.
- One structural singularity of the building structure was the span of the post-tensioned slabs; whose design was governed primarily by Serviceability Limit States.
- The building is located in a central neighborhood of the city, which adds complexity to supply of materials and services.

This identification allowed conceiving specific information pipelines ranging from measurements to decision-making tools.

c. User-interface

The user interface is a dashboard based on a game engine developed in Unity [43]. In its present form, the dashboard is based on: the IFC Geometry, the corresponding link to an IoT platform, appropriate and modular links with an expandable toolkit conceived for providing assistance at several stages (design, construction and maintenance). Thus, different tools contribute with data to the user in many different forms. The end-user can thus leverage this information for decision making. Assets are twinned with interoperable IFC geometrical entities and on top of this geometry, the set of tools provide/collect information and analysis for decision-making.

Fig. 3 shows a geometrical representation of the building (IFC). In its present version, using a 3D geospatial visualization web tool [44], the building can be placed realistically within its real location (other geolocation visualization tools are also under study). In the same figure, a structural element is selected and information about this element is retrieved (window at the right part of Fig. 3).

Fig. 3. The building displayed in the developed dashboard.

On the other hand, a ribbon with a set of tools in the form of icons is also displayed. These tools perform specific functionalities and represent the core of the initial conception of the platform developed within the project. The expandable toolkit of the platform presently includes a series of functionalities listed in Table 2. More specifically, the functionalities related to construction are those emphasized in this paper.

The IoT platform [45] represents a very important core of the system. It enables the communication between the gathered data and the dashboard. This IoT platform is scalable, secure, open-source, and patent-free, which also represent a fundamental connection with all tools (or potential future tools to be developed). It receives connections over various network protocols (i.e. HTTP, MQTT, WebSocket, CoAP) and consists of multiple microservices (MS) with separate and well-defined responsibilities. Examples of MS are management of users and authentication concerns, management of things and channels or tailor-made storage infrastructure. These MS can be run in many different ways according to the use case needs. They can be run locally or in the cloud, on premise or off-premise. They can be run as a composition of Docker containers or as standalone applications on the local host computer.

d. Integration frameworks

For the sake of connecting data generated from various sources in the same asset (geometry, IoT, different tools, simulations), Knowledge Graphs (KG) are used [46]. A KG is a type of database that is used to store and represent information as a network of interconnected entities and their relationships to each other. This allows for more sophisticated and nuanced information to be represented and queried than would be possible with a traditional database. KG are visual and functional entities aimed at providing a contextual understanding of the connection between data. They are an interlinked set of facts that describe real-world entities events or things, and their interrelations are written in human- and machine-understandable formats. The particularity of these graphs is that they link data from disparate sources by enriching the model with taxonomies and ontologies that add layers of information that upraise the level of abstraction in the data. KG are presently used in many other applications such as semantic search, network analysis or natural language models.

e. Expandable toolkit

Table 2
A set of integrated functionalities within the dashboard.

Name	Use	Functionality
BRICS	Design	Knowledge base for identifying design patterns from past digital twin data. These design patterns are formulated in practical rules that can be queried by designers to improve the productivity, resource efficiency, and safety of their designs.
GEN	Design	Generative design methods that allow designers to automatically generate alternatives based on a specific set of input parameters.
EBD	Design	The EBD tool supports the AEC early project stage by using collated historic data (from past project designs and the built physical infrastructure) from an existing knowledge base to provide design predictions, warnings and recommendations.
4DV-D	Design	This application allows to visualize the effects of specific design options on productivity, resource efficiency, and safety. Different options can be compared with each other by visualizing projected construction sequences
DES	Construction	A tool to set-up discrete event based stochastic simulations of planned construction activities and site layouts. The tool uses stochastic productivity data.
4DV-C	Construction	A 4D tool visualizing past construction activities based on activities tracked by the digital twin platform. The tool allows to plan future construction sequences and site layout options based on accurately mapped past activities.
SMT	Construction	An application that allows safety managers to understand possible safety hazards on site and to analyze past construction activities without being able to target specific workers.
CMT	Construction	Software that allows for establishing and maintaining consistency among requirements, design, configured items, and associated construction, operations and maintenance data, equipment, and other enablers throughout the project lifecycle.
MatchFEM	Design/Construction/ Maintenance	Implemented methods that allow to adjust input parameters for different multi-physics simulations within the DT. These methods allow for the accurate representation of behavioral digital twins.
RISA	Maintenance	Visualization tool allowing for the detailed understanding of an asset's status for designing optimized maintenance plans.
GISI	Maintenance	A GIS tool allowing asset managers to keep track of the digital twin predicted status of multiple assets.

On the other hand, within the frame of the project, an ontological suite has been developed [47,48]. It is meant to conceptualize the knowledge of DTs of civil infrastructure projects through their entire lifecycle with special emphasis on the construction phase, thus contributing towards a common understanding of the dimensions of construction digital twins. Table 2 summarizes the tools developed by the moment this paper is submitted (with potential expanding capabilities for the future).

4. Construction schedule and twinning actions

Access to the construction site was agreed upon with owners and managers under certain conditions in space and in time. The period during which the access was granted was limited. In addition, the premises in which data-collection was allowed were limited to the nine-story module highlighted in Fig. 2 and presented in more detail in Fig. 4.

All actions related to the development of information pipelines had to be chosen as a suite of measurements from the site that could be tracked virtually in the twinned version of the erection of the RC concrete structure of Fig. 4. The challenge was to find ways of measuring how the modular conception of a digital twin interface could help managers of the construction site to improve key aspects for the sector such as safety, productivity, resource efficiency.

The planned construction phase of such module showed predictable sequential progress with main repetitive tasks at each story: formwork set up, reinforcement placement, concrete pouring, tendons post-tensioning, and formwork removal. In this scenario, the development of information pipelines was conceived as a way to track these repetitive tasks. Thus, the building provided an interesting insight and developmental facilitating construction progress monitoring, quality control, and data-driven decision-making for upcoming tasks with previously collected data.

The construction of the structure was finished according to schedule within six months. Fig. 5 presents the calendar of the casting of columns and slabs. Roughly erection of columns was scheduled every three weeks. The performed actions for data-collection, were thus matched to this calendar as much as possible. The performed tasks for data-collection are the following: i) tracking of the crane load spatial position, ii) measuring longitudinal strains during post-tensioning of the slab iii) laser scanning of the slabs for deflection checking as well as for As-built vs As-Design checks, iv) concrete temperature monitoring for maturity index, v) formwork accelerations during vibration of columns and vi) sequential tracking using IoT-connected mobile phones.

In Fig. 6, an overview of the construction process is presented. Specifically, the casting of a column using a concrete bucket, the placement of passive and active reinforcement, and a perspective of the module under twinning.

5. From the site to the dashboard. Pipelines of information

Influenced by site access challenges, the information pipeline design was molded by time and space constraints. The design of pipelines had two major constraints.

- The information should flow from the site (source) to an end-user interface able to show relevant indicators of performance (delta). As a result, managers could identify margins of improvement of this construction process at a regular basis. The motivation was particularly based on increasing productivity, resource efficiency, and/or safety using a set of performance and key performance indicators [24].
- Access to the building was granted to researchers at a particular time during construction when specific actions were held. During the in situ casting of the RC structure, the construction focuses on structural materials (concrete and reinforcement), members

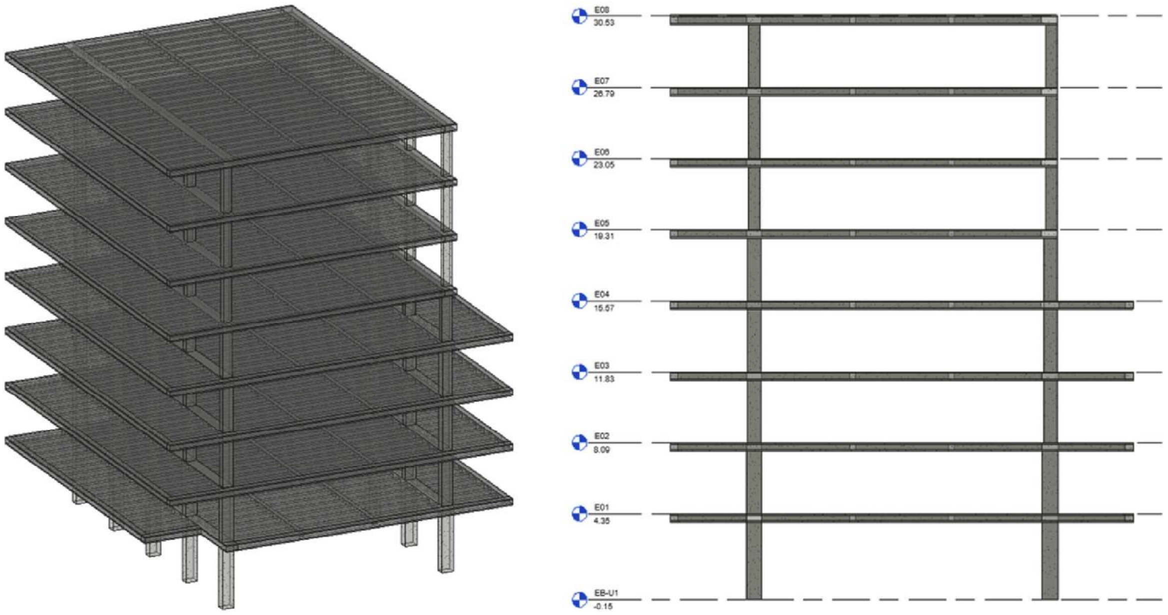


Fig. 4. Premises in which data-collection was allowed.

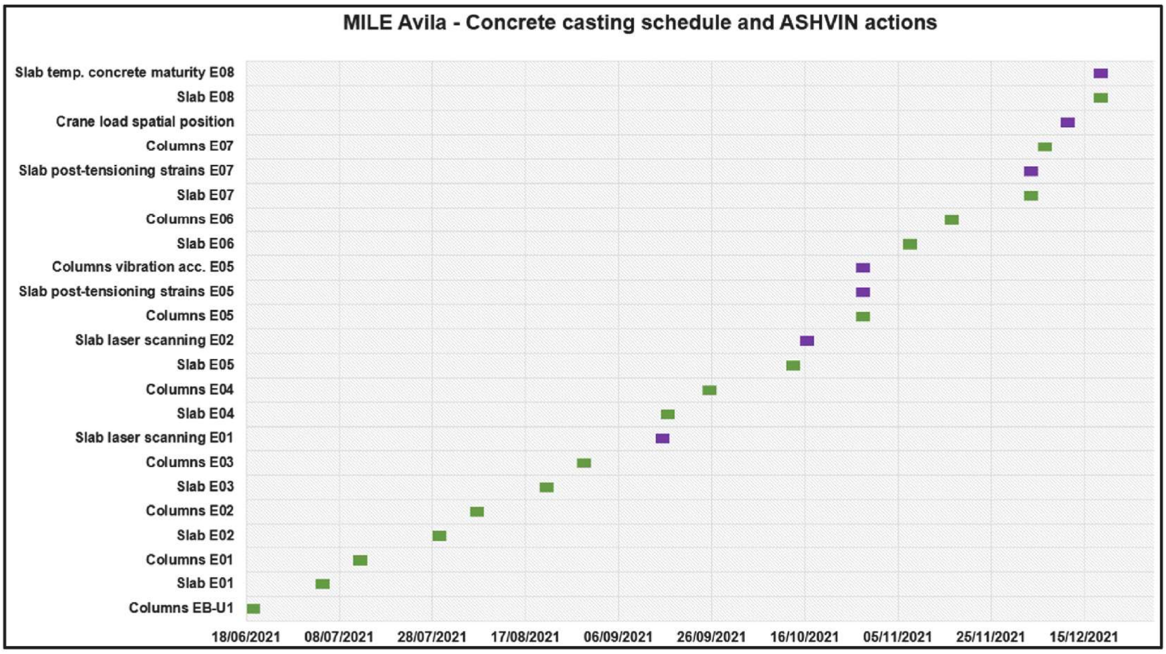


Fig. 5. Concrete casting schedule and ASHVIN actions.

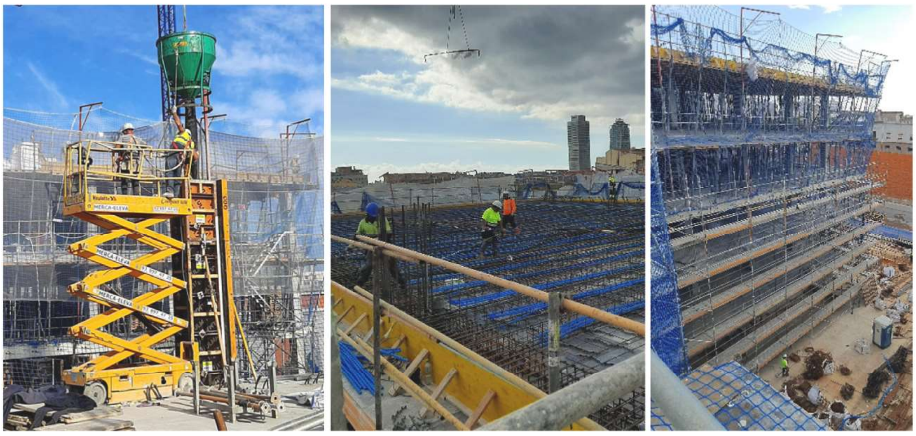


Fig. 6. Overview of the construction process.

(beams, columns) and components (slabs, floors, stories) were the primary source of information. Special emphasis was placed on the concrete supply chain within the defined construction period.

Sensors, images, point clouds or other in situ gathered annotations can be collected during construction tasks. In this particular case, only sensors and point clouds were selected to track easily key material characteristics, key positions of equipment and key 3D representations of the whole structure under erection. Images were not used systematically as a data-collection technique in this particular twinning process of the structure construction.

The information flow from data-collection to performance indicators is depicted in Fig. 7. The collected data from the construction site is treated through APIs and subsequently translated to project-specific KPIs on the centralized dashboard. The designed dashboard represents a DT platform in which value of the data flow is extracted from the source to the delta. In this particular case study, measurements are integrated and stored orderly using IoT [45], different types of simulations are integrated using tools from the kit (MatchFEM and DES, Table 2) and a set of performance indicators are linked to these information pipelines.

In Table 3, a description of six different pipelines of information is provided. Information within these pipelines flow from the source (data-collection) to performance indicators (delta). Data process by means of several tools embedded in the data flow are used. Details on each pipeline are provided in 5.1–5.6. Ideally, based on results obtained at a given floor, decisions and actions could be taken by constructors for subsequent floors. The life cycle of information was roughly three weeks. These specific pipelines suggested that all information analysis required a weekly update of the measurements, tools and visualization of results.

5.1. *Concrete pouring process (PCL)*

A tower crane executed the concrete pouring process for walls and beams. Ready, adequately-mixed concrete was delivered to the construction site by third-party trucks that arrived at the site many times daily. This data collection is only concerned with times

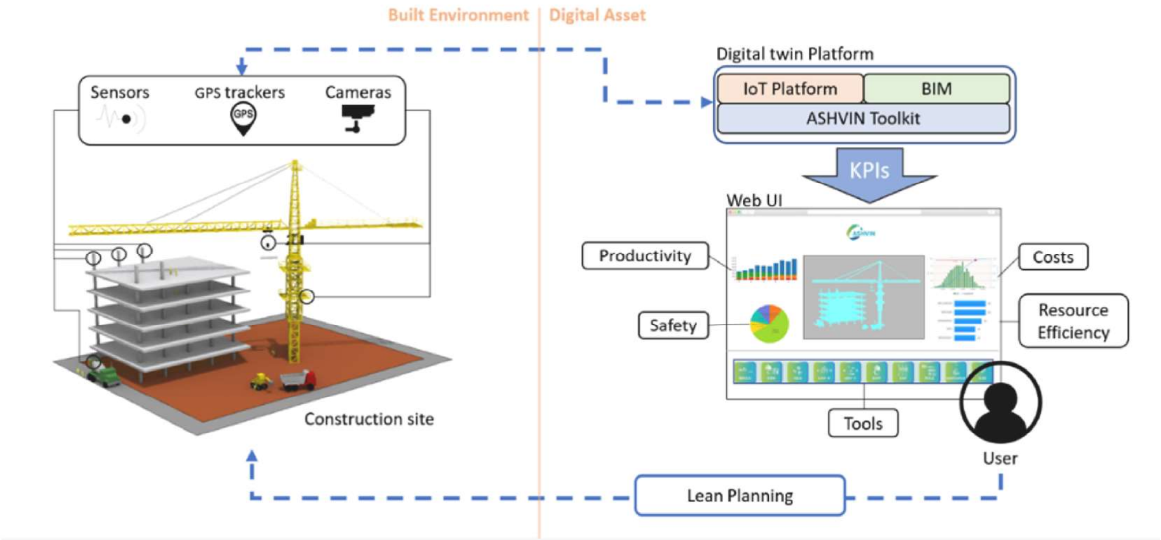


Fig. 7. Organization of the information.

Table 3
Information pipelines implemented during twinning of the building.

Name	Data collection	Stakeholders	Simulation	Application	Performance indicator [24]
PCL	Spatial position of the crane load. IMU sensors	Crane operators/ Construction managers/Concrete supplier	Discrete Event Simulation	Analysis of the sequence of concrete casting. Identification of bottlenecks and potential improvement	Construction duration, Workers productivity, Crane productivity, Utilization rate crane, safety factor and personnel costs
LS	Longitudinal strain during slab post-tensioning. Strain gauges	Post-tensioning suppliers/Construction managers	Structural analysis of the tensioning process	Timely analysis of adequate tensioning of the slabs. Component properties	Integrity of structural components, strength of structural components, productivity
SD	Slab deflection using laser scanning	Formwork staff/ Construction managers	Point cloud analysis	Timely control of the slab deflection.	Percentage Plan Complete, Productivity, Strength of structural components
CM	Temp. Of fresh concrete using temp sensors.	Concrete suppliers/ Construction managers	Nonlinear time-dependent structural analysis	Advanced analysis may allow to reducing formworks and accelerate unshoring	Integrity of structural components, strength of structural components, productivity
AV	Acceleration during vibration using accelerometers.	Concrete suppliers/ Casting staff/ Construction managers	Signal processing of the measurements	Identification of adequate vibration time (energy-wise, quality-wise)	Productivity, adequate concrete vibration, energy consumption and percentage plan completed
CPM	Construction progress monitoring using mobile app data entry.	Construction managers	N/A	Observation and evaluation of the expected project's progress and performance	Productivity, percentage plan completed

elapsing once the truck was on the site premises and a crane lifted a bucket from the building to the street level next to the arriving truck. The bucket was prepared and fresh concrete was poured into the bucket. Sequentially, the crane lifted the bucket up and poured the concrete into the corresponding formwork with the help of workers. This was a repetitive process of the four actions: Filling, Lifting up, Pouring concrete, and Lifting down. The whole process depended on timely concrete deliveries, as early or late deliveries could affect the quality and efficiency.

Sensors were implemented to track the position of the bucket during the repetitive process. Time series data with coordinates were gathered for one week. A sensor system consisting of an accelerometer, a gyroscope, a global positioning system (GPS) tracker, and a barometer was attached to the crane hook to collect the following data with a timestamp at a frequency rate of 4 Hz: 3-axis acceleration, 3-axis angular velocity, longitude/latitude/altitude, and altitude by air pressure. The collected data was transferred to the IoT platform as a comma-separated-value (csv) file.

A camera recorded the construction process by video for data labeling and validation. Overall, data for 98 min and 52 s was analyzed for detecting activity durations. Sliding window consisting of eight data points with an overlap of 50 % were calculated and labelled manually with the help of the recorded video. Following the labeling, the data was analyzed by five different supervised machine learning classifiers for activity recognition. The performance of Naïve Bayes, Decision Tree, k-nearest neighbor, support vector machine, and Random Forest was compared to detect the best classifier according to a 10-fold cross validation. The Random Forest classifier performed the best, with an accuracy of 93.27 % and was used for further analysis. This is the core of the Discrete Event Simulations applied in this particular digital twin.

Following the data classification, results were post-processed automatically by defined logical rules. E.g. the four actions have to be always in the same sequence (Filling, Lifting up, Pouring concrete, and Lifting down). As each sliding window consisting of eight data points with an overlap of 50 % equals 1 s, the calculation of individual durations for each action was enabled. The detected data-based durations were verified to check for credibility of the results and the result was a reliable set of action durations regarding the execution of the concrete pouring. Fig. 8 presents a timeline for the detected durations of the first repetitions of the four actions. Each duration differs for each repetition as the actions are dynamic.

Due to the uncertain nature of activity durations, static parameters are unsuitable for representing processes in a virtual environment [49]. Therefore, based on the extracted durations, stochastic productivity modeling was applied to determine suitable probability density functions (PDFs) as input parameters for activity durations in a discrete event simulation. The maximum likelihood estimation method optimized the respective parameters for different probability functions. Next, Goodness-of-Fit statistics compared the determined PDFs with the cumulative set of durations. These Goodness-of-Fit statistics calculate the deviation of possible PDFs to the set of durations and the PDF with the lowest deviation was chosen for further analysis. The identified PDFs were validated by hypothesis test and no statistically significant difference was detected according to a significance level of 0.05. Thus, the PDFs were validated and represent valid input parameters for the discrete event simulation. A two-sided hypothesis test validated the data-driven discrete event simulation model to ensure credibility of the forecasts. Fig. 8 shows a sequence of time measurement activities under scrutiny (Filling, Lifting up, Pouring concrete, and Lifting down). A more detailed description of the data analysis can be found in Refs. [50,51].

Following the validation, the simulations were used to test a multitude of different construction options [50]. E.g., different resource allocations or delivery intervals can be tested in a virtual environment to manage ongoing construction works based on real-time data and by including lean construction principles. Additionally, weather forecasts have been incorporated. In the simulation, productivity, resource-efficiency, and safety-related PIs are forecasted. These include the construction duration, productivity rates for workers and crane, the utilization rate of the crane, a safety factor based on weather conditions, and the personnel costs. These data-driven forecasted PIs provided a meaningful information basis to facilitate the decision-making process for construction management. The estimated KPIs and the processes for each option is expected to be visualized by bar charts and 4D visualizations in the functional dashboard under development. It is aimed at ensuring continuous workflows for the resources through just-in-time deliveries. The evaluation of the performance indicators offers detailed information about the estimated outcomes and, thus, constitutes a basis for the decision-making process in planning meetings. Hence, data-driven instead of experience-driven decision-making is enabled. If the construction work proceeds according to the data-driven decision-making, during construction continuously new data can be collected to update the activity durations until works are finished. It has been proven that continuous data-collection and updating activity durations are necessary to maintain a valid model [51]. Fig. 9 illustrates the detailed information pipeline for managing the concrete pouring process.

5.2. Longitudinal strain (LS) in unidirectional slabs

During the post-tensioning of tendons belonging to the slabs, a polyester linear wire strain gauge (PL-90-11) with mild steel compensation, a resistance of 120 Ω, and a strain limit of 2 %, was installed in the center of the span in the longitudinal direction. Measures collected from the strain gauges were locally stored and then, python scripts were developed to process the raw data. Processed data was thus uploaded to the IoT platform using HTTPS protocols. The output of a strain gauge is in the form of a change in electrical resistance, which is proportional to the amount of strain applied to the gauge. Maximum values of strains were expected at mid-span on predetermined points. Measurements were taken for slabs at E05 and E07 building levels. Data-collection started before the initiation of tendons stressing and ended after the last tensioning. Fig. 10 shows the strains in the slab produced by the post-tensioning during 3,5 h of data-collection at level E07. Measures presented a noticeable increment when the tensioning was approaching to the zone in which the strain gauges were installed.

The post-tensioning procedure was done with the slab supported on the formwork, therefore, the instant variation of strains was produced exclusively by the applied axial force. The tensioning force is specified by the project engineer and its relevant to verify its correct execution. Using specific tools for structural analysis [52], the expected strains during tensioning can be matched against the strains measured at the construction site, providing a method to control the quality of the slab post-tensioning task. Variation of the strains for the post-tensioning of the slab at the E07 level was 3,67 με. Through parametric models constructed with Karamba 3D, a

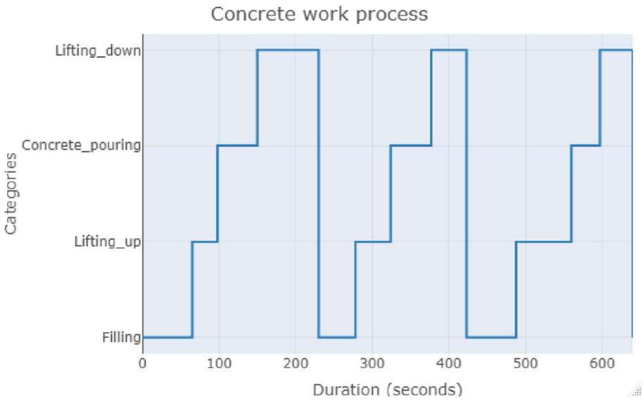


Fig. 8. Timeline for the detected durations.

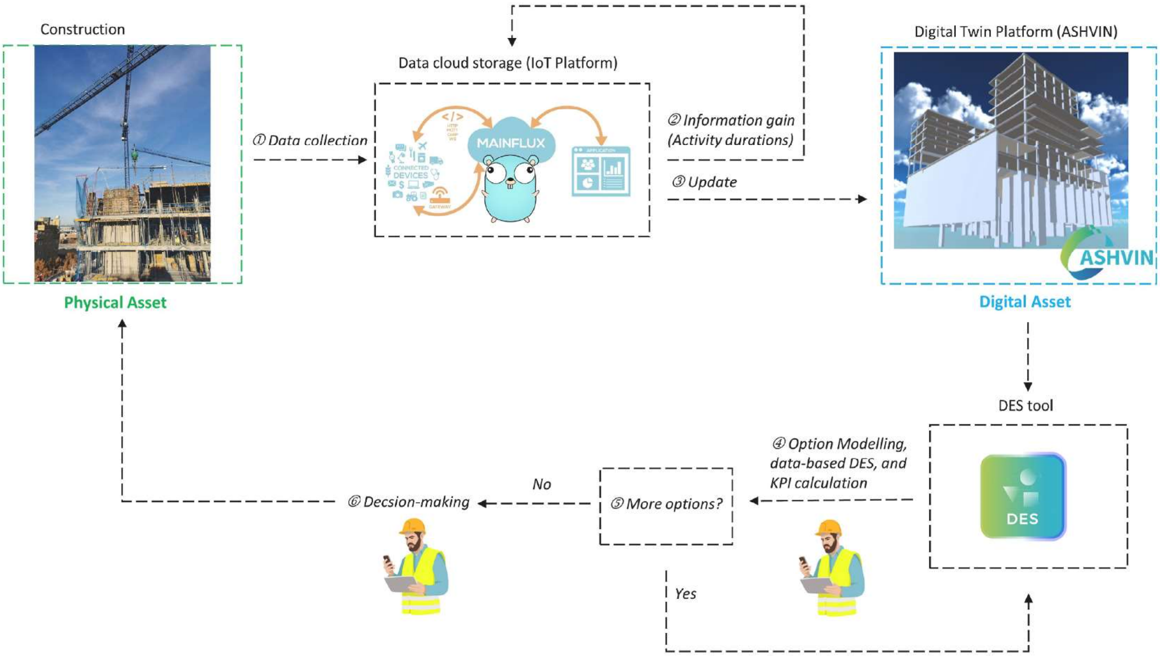


Fig. 9. Concrete pouring process (PCL) information pipeline.

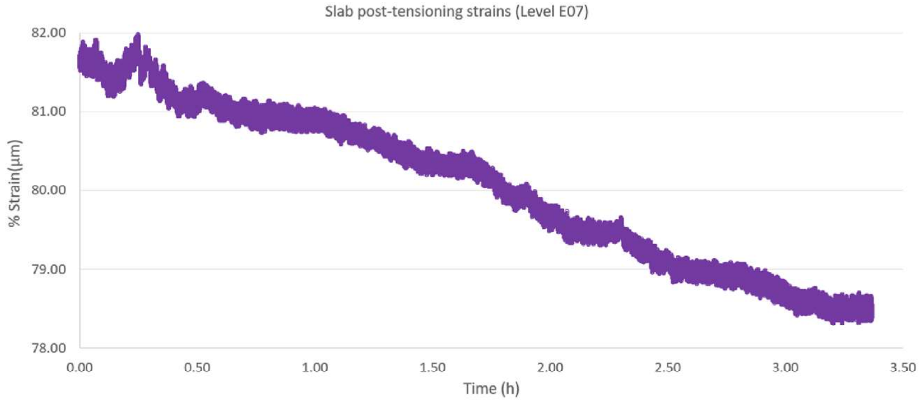


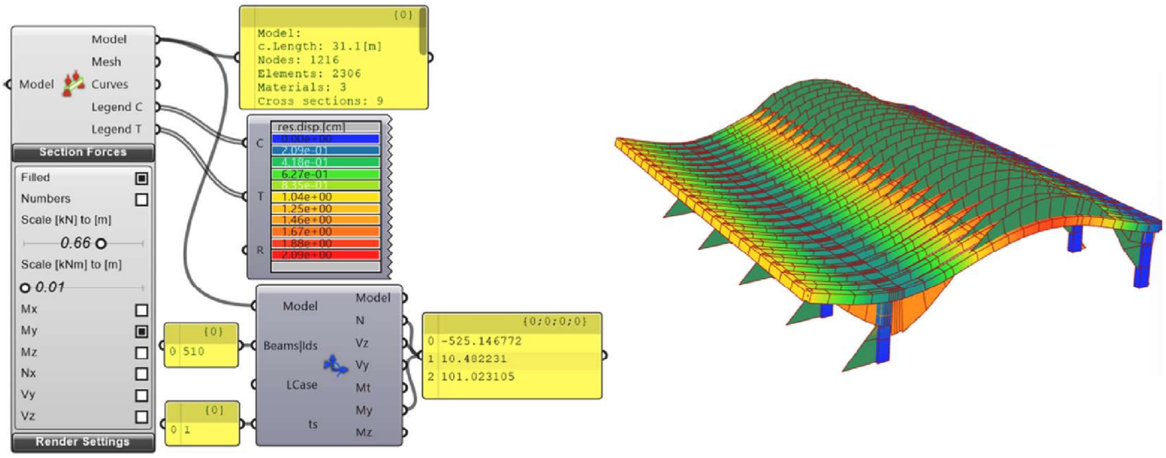
Fig. 10. Slab post-tensioning strains at level E07.

plug-in for the Grasshopper licensed software, it was possible to check the variation of the strains with the results of a predictive simulation. Fig. 11 presents the generated structural analysis model for the MILE-building slabs.

The model estimated in 4,66 με the strain produced by the post-tensioning at the top of the slab for the E07 building level, representing 127 % of the measured strain (3.67 με). In a sequential post-tensioning process with different tendons, forces are distributed more smoothly across the slab, which indicates a better structural performance than expected, and an acceptable gain of strength of the concrete. Structural analysis models and specific performance indicators of component properties can be fed with this relevant information during construction. Fig. 12 illustrates the pipeline of information. The slab strains output is verified and validated through a Structural Analysis model using the applications that enable the use of simulations within the DT [33]. Thus, the measured against the expected values are compared. Results are computed to determine KPIs related to the post-tensioning task. Integrity and strength of the slabs during the tensioning of the cables and the productivity of the activity are available for construction managers enabling data-driven decision-making.

5.3. *Slab deflection (SD) during sequential construction*

During the erection of the module under study, concrete slabs were sequentially and coordinately shored, casted, matured, post-tensioned and unshored for 9 floors. During the casting and hardening processes, the load related to fresh concrete and formwork was transferred from temporary supports (shores) to the slab underneath. That slab was loaded abnormally during construction (carrying a load that after unshoring is transferred to the columns). This effect is worth analyzing by structural engineers during the design stage of the building as well as by construction managers. Therefore, establishing a procedure to monitor the erection process could give valuable information to the stakeholders involved.



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2.09e+00

Filled ☒
Numbers ☐
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Scale [kNm] to [m] 0.01
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My ☒
Mz ☐
Nx ☐
Vy ☐
Vz ☐

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2 101.023105
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Fig. 11. Karamba 3D structural model for post-tensioning of the slab at level E07.

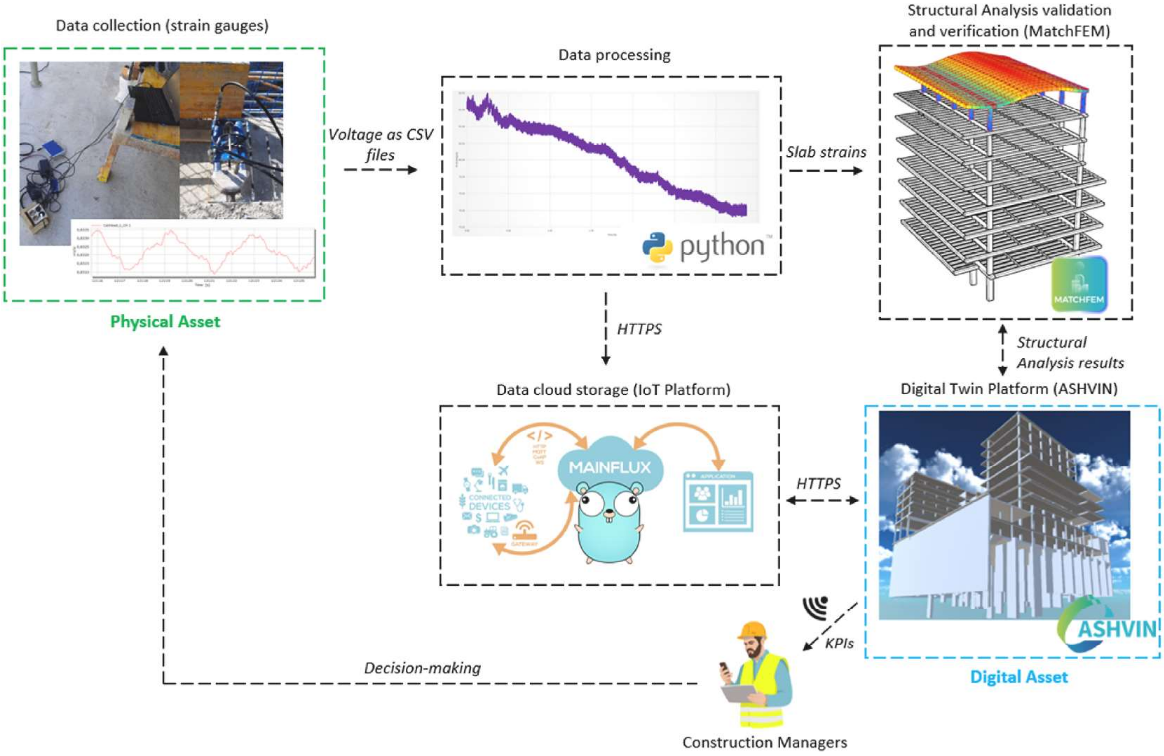


Fig. 12. Slab post-tensioning longitudinal strains (LS) information pipeline.

To this purpose, a Terrestrial Laser Scanner (TLS) was used to sequentially generate point clouds related to all slabs carrying the load of the temporary supports and after unshoring (no direct load applied). Two measurements were performed on each slab (See Fig. 13).

- The first measurement is performed right after casting concrete on the upper shored slab. The measurement episode was composed of two scanning positions to cover the whole area of the floor. Using a set of target spheres whose position is controlled, scans performed in different episodes can be registered into a single point cloud.
- The second measurement is performed after unshoring the upper slab. The position of the spheres was carefully marked to allow replicability from one measurement to another.

The scanner measurements were taken with a density of one point every 3 mm at a distance of 10 m. For each point captured, an average of 6 readings was taken to reduce the potential impact of unexpected deviations.

These measurements allow managers to monitor the erection process from two perspectives: On the one hand, measurements corresponding to shored and unshored scenarios are co-registered and compared to the design geometric model to calculate the slab deflections. Results are verified against as-designed structural models, providing guidance about whether the structural performance and safety of the slab are within the established design bounds. On the other hand, time-stamped measurements allow for correlating the erection timing with structural performance, providing a hint of whether the concrete setting times before unshoring are being

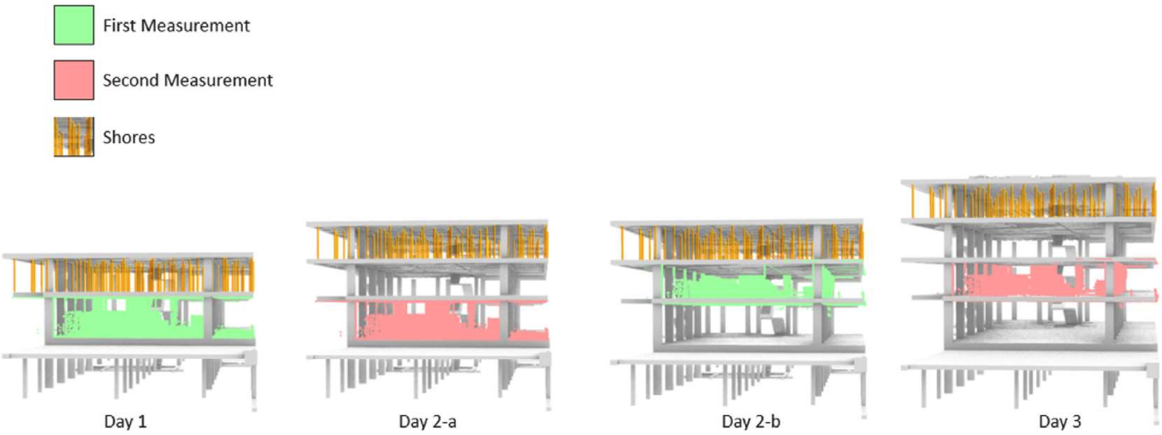


Fig. 13. Sequential pointcloud measurements of the erection process of the building.

correctly executed. The toolkit includes applications to carry out time schedules as well as performing structural analyses. This represents a means to evaluate performance based on specific comparisons delivered to construction managers, structural engineers, and formwork staff to evaluate and enhance erection works control. Fig. 14 illustrates details about this particular pipeline of information. The contribution of the pipeline to the digital twin of the building will be visualized in the dashboard through a set of KPIs regarding the Percentage Plan Complete (PPC), The productivity rate and the strength of structural components.

5.4. Concrete maturity (CM) and its effect on construction sequences

Right after the pouring of the slab in the E08 building level, three sensors were embedded in the fresh concrete to monitor its temperature during the hardening process. Two of the sensors were Thermocouples K, with a range from 0 °C to 400 °C and an error of ±2.2 °C. The other was a DS18B20, a waterproof digital sensor that uses a Wire-1 protocol to communicate and collect temperature data in a range between −55 °C to 125 °C with an error of ±0.5 °C. Concrete temperature evolution was collected for 34 h by Thermocouples K and 30 h by DS18B20 sensor, limited by the power banks that supplied the energy. Fig. 15 shows the collected data from the three temperature sensors.

Monitoring the concrete temperature at early ages provides an accurate estimation of the compressive strength evolution by the implementation of the maturity method. The widely-used methodology is defined by the ASTM C10741, which assumes a nonlinear relationship between concrete temperature and the evolution of the concrete compressive strength. Collected temperature measures and the ASTM standard can be set up within Grasshopper Python scripts to predict the concrete compressive strength evolution as presented in Fig. 16. Data was retrieved from the IoT platform directly to Grasshopper using a developed micro-service.

With a reliable estimation of the compressive strength evolution at early ages, is possible to perform structural analysis simulations using the predicted material property within the same parametric software. Using Karamba 3D, a structural engineering plug-in for Grasshopper, the concrete material properties updated with the estimated compressive strength as input, calibrating the elastic

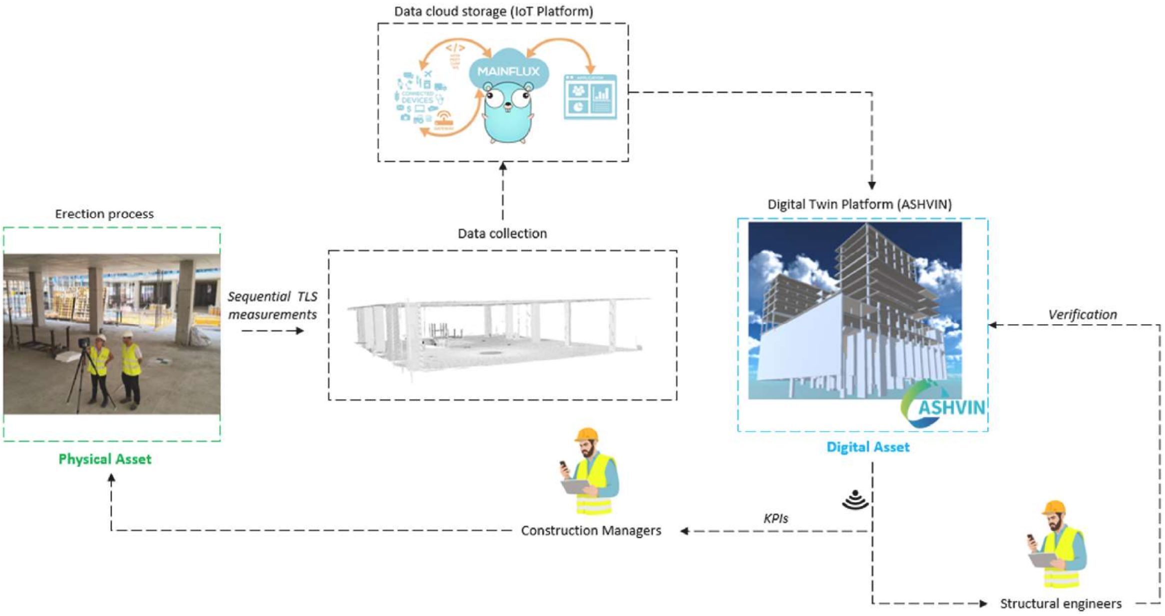


Fig. 14. TLS-based sequential construction monitoring information pipeline.

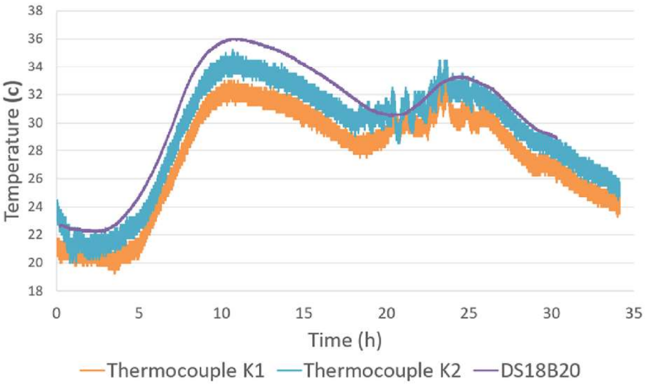


Fig. 15. Collected data from temperature sensors.

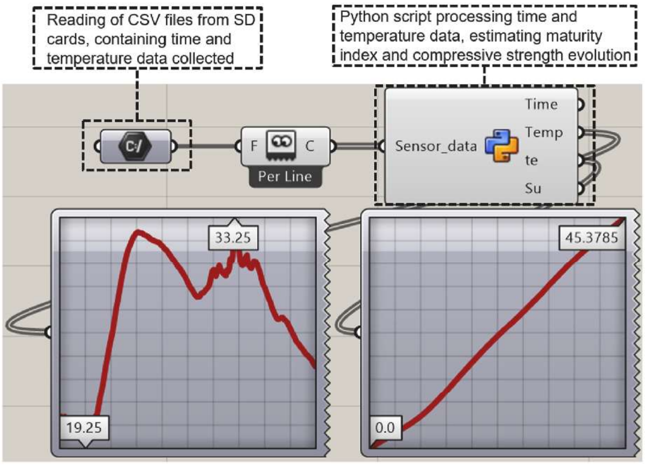
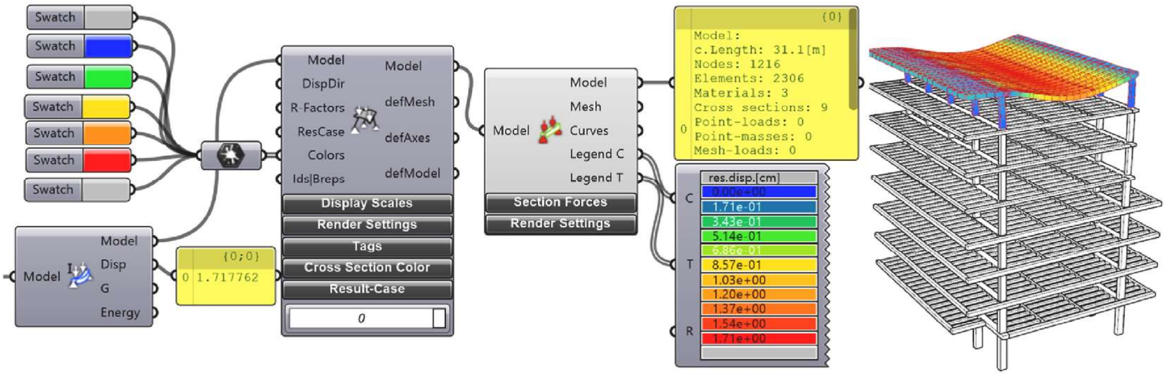


Fig. 16. Maturity and compressive strength estimation from temperature data within Grasshopper.

young modulus according to the maturity of the concrete [14]. The structural model is then assembled to check the maximum deflections at the slab, as shown in Fig. 17.

By implementing frameworks within one of the tools presented in Table 2 such as MatchFEM [52], a regular update with site measurements is possible. This provides valuable information to technical supervisors and construction managers. This enables them to make more informed decisions, such as the initiation of formwork removal or validating the quality of slab casting. Getting a good estimation of the concrete compressive strength at early ages may have benefits for construction management. The initiation of striking of formwork and tendons stressing are strongly related to the concrete compressive strength. With collected data from the construction site, information is channeled to various structural models with updated data to perform right-time structural analysis. This may result in time and cost-saving if tasks can be initiated earlier than expected. Fig. 18 illustrates details about this particular pipeline of information. Concrete temperature data at early ages is stored as CSV files in SD cards at the project site. Then, measures are exported as inputs to a Python script that implements the standard ASTM C1074-19e to predict the concrete compressive strength evolution, following the maturity index curve of the concrete specific mix. In addition, Python routines upload the temperature data and the compressive strength evolution to the Mainflux IoT platform through HTTPS protocols.



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Nodes: 1216
Elements: 2306
Materials: 3
Cross sections: 9
Point-loads: 0
Point-masses: 0
Mesh-loads: 0
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Fig. 17. Karamba 3D slab structural model for checking maximum deflections.

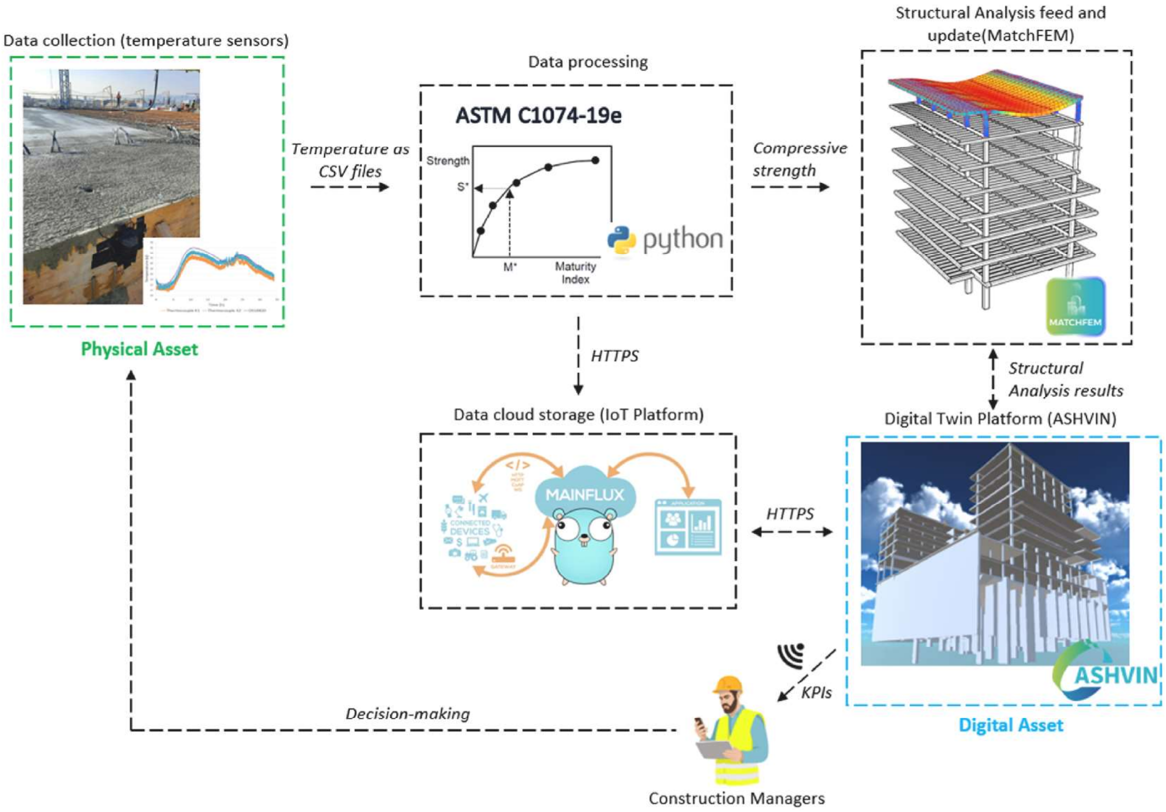

Fig. 18. Slab concrete maturity (CM) information pipeline.

The output data feeds and update the Structural Analysis model by means of the MatchFEM tool. Results and KPIs such as the integrity of the slab, the concrete compressive strength evolution and the productivity of the related construction tasks are estimated within the Digital Twin platform, being accessible via Wi-Fi to the construction managers.

5.5. Vibration of fresh concrete (AV) during column casting

Vibration of the concrete helps to eliminate air pockets by causing the mix to settle and allowing the air to rise to the surface where it can escape. The process of consolidation also helps to ensure that the concrete is evenly distributed within the formwork or mold, which improves the overall strength and durability of the final structure. During the vibration of the columns, acceleration was measured as an indirect measurement of the casting process with several applications. For this purpose, high-sensitivity Kenshin-kun MEMS accelerometers with a temperature operating range from −20 °C to 60 °C and a measurement range of ± 2G, were mounted on columns formworks. This allowed recording the accelerations produced during the routine procedure performed by operators, as presented in Fig. 19.

While being poured, concrete retains around 20 % of entrapped air depending on the mix, the slump, the size and shape of the formwork, the number of reinforcement bars, and the concrete pouring technique. Consolidating the concrete is a relatively tailor-made activity in each case. In the accessed module, ten columns per floor on a total of nine stories were poured under very similar conditions, which resulted in an interesting sample of analysis. Fig. 20 presents the recorded formwork accelerations for two of the columns during the vibration of the fresh concrete.

Formwork accelerations during the vibration of the columns were locally stored. Then, a Python script which is set up to another tool called CMT (see Table 2), processes the data and estimates the vibration time of each column, identifying the passive intervals where accelerometers are not being excited by the immersion vibrators. Accelerometers data and output results are uploaded to the IoT platform by means of HTTPS protocols.

Usually, construction engineers define a range of time for the vibration of columns, to avoid lack of consolidation or over-consolidation. The objective of this pipeline was to track the vibration time in all identical elements in order to analyze: component properties, energy consumption and percentage plan completed. Through an application of construction management as well as the measured accelerations during column casting, users can track the actual vibration time of each column, providing valuable data to construction managers for checking the efficiency of the task execution, avoiding overuse of energy and ensuring quality control. Based on the acceptable time range of consolidation of the columns' concrete (which is specified by construction engineers), results also indicate the quality of the performed task in terms of safety (adequate component materials) and in terms of resource efficiency (adequate use of energy on the site). Fig. 21 illustrates details about this particular pipeline of information.

Fig. 19. Collection of formwork accelerations during vibration of columns concrete.

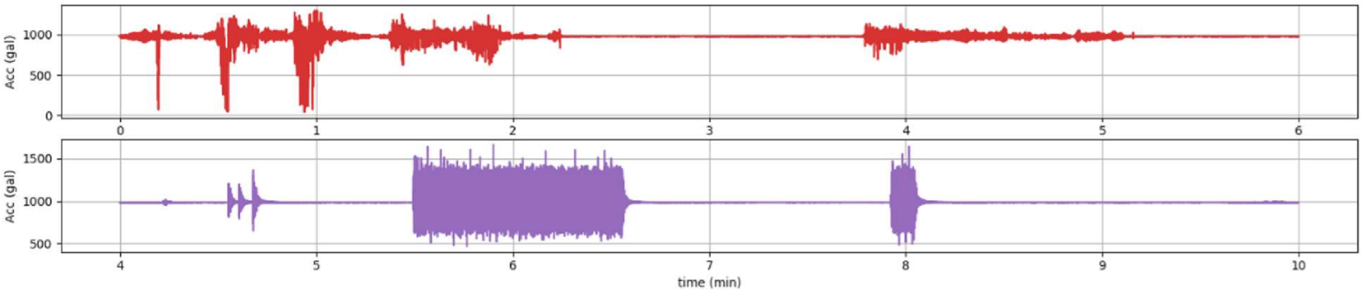

Fig. 20. Accelerations of formworks during vibration of columns concrete.

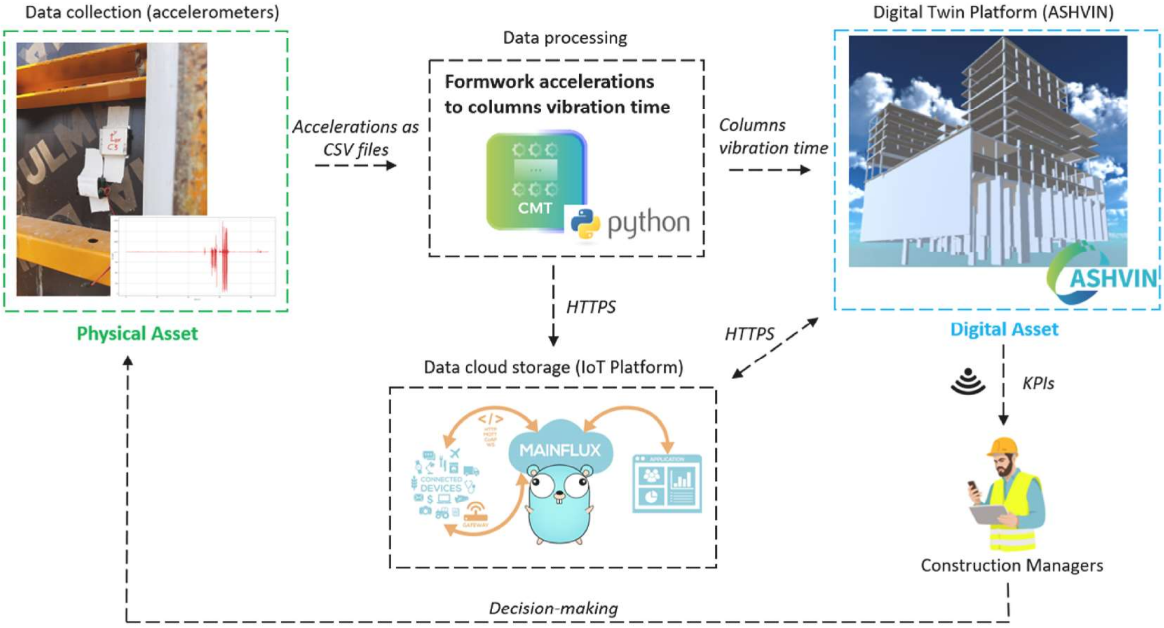

Fig. 21. Vibration of fresh concrete (AV) during column casting information pipeline.

5.6. *Construction progress monitoring (CPM)*

A series of procedures were employed to contribute to supervision of the project's progress and achievements. Discrepancies from the initial plan and modified implementations can be tracked accordingly. This entails evaluating the project's development by means of inspections and contrasting it against the project plan to ascertain whether the anticipated outcomes are being accomplished. In recent years, the continuous pursuit of improving automation in construction progress monitoring has directed efforts to integrate advanced technologies such as computer vision, laser scanning, photogrammetry, and augmented reality [36–42]. While research in cutting-edge areas pushes forward the knowledge boundaries, the vast majority of construction sites rely on manual crafted procedures Most existing approaches rely on manual input, whose data entry is time-consuming with its associated overall cost [53–55]. In order to contribute to the set of tools of this particular case study, a generic mobile application for assessing the project progress performance is proposed based on visual inspection. Fig. 22 shows the general usability of such application.

The mobile app is capable of storing IFC-BIM metadata of building elements and tasks and performing bidirectional communications with an IoT platform. Construction managers or technical assistants update the status of the tasks by visual inspection after completion. The new status of the task, along with its timestamp is sent to the IoT platform. The app operation workflow is described in Fig. 23. Fig. 24 shows an example of the message that is sent from the mobile app to the IoT platform in JSON format through HTTPS communication protocols.

The message in JSON format includes the communication channel between the mobile app and the IoT platform, the subtopic that indicates the building level of the BIM element, the user that is the person who sends the data, the type of protocol for network requests and data exchange, the name and ID of the BIM element and the related tasks, the timestamp of the message, and the status of the task. 4DV-C tool retrieves the message from the IoT platform. Then, users can visualize the planned and actual construction progress on a split screen in the DT platform. Based on the planned and actual completed times of tasks, KPIs for productivity and percentage plan completed are estimated, enabling informed decision-making for construction managers. This information pipeline paves the way for including functionalities within the DT platform that enable advanced project performance assessment techniques, such as Discrete Event Simulation, with timely and valuable data collected on the construction site and integrated with IFC-based BIM models.

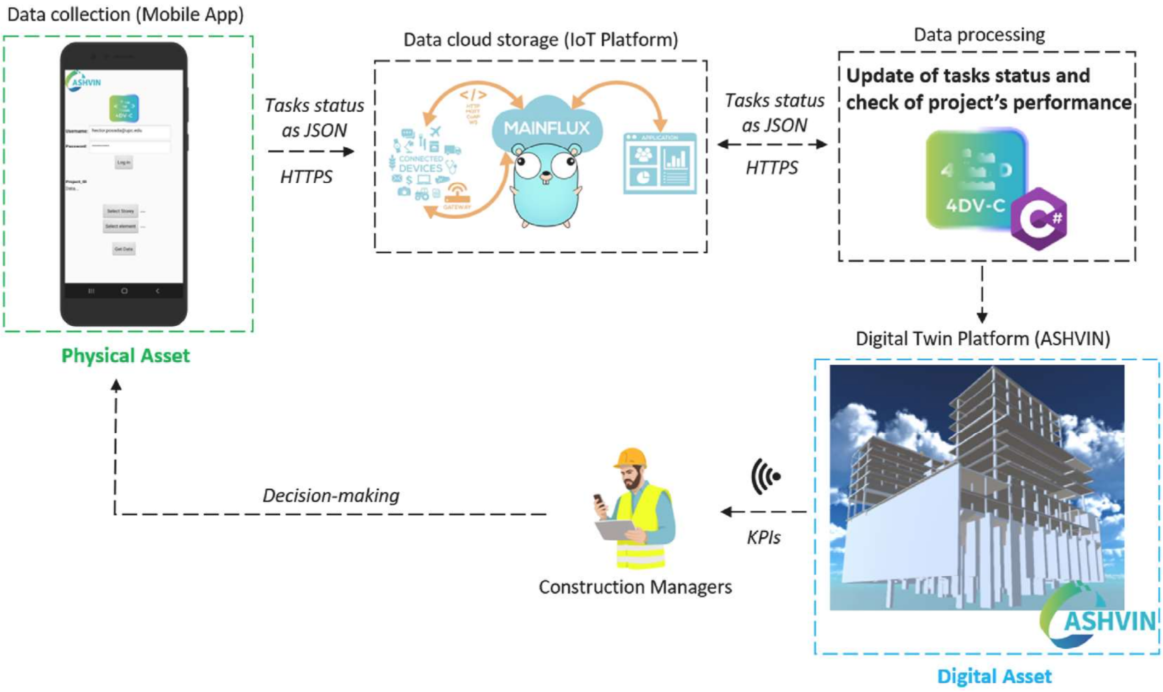

Fig. 22. Concrete progress monitoring (CPM) information pipeline.

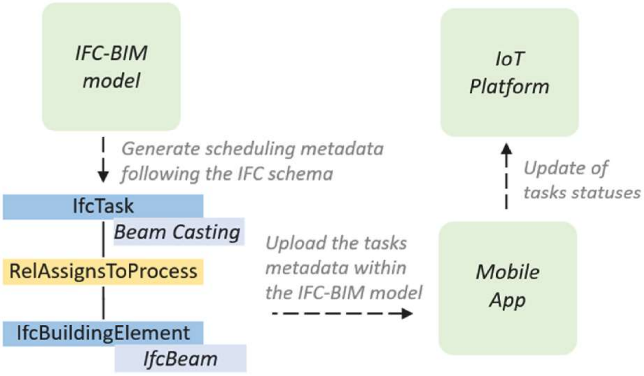

Fig. 23. Mobile app operation workflow.

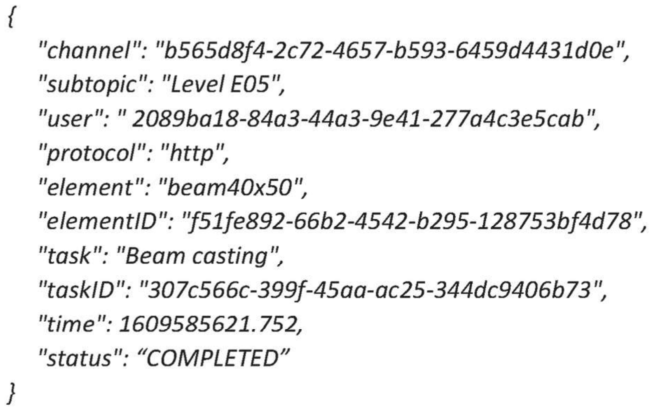

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Fig. 24. Mobile app message to the IoT platform in JSON format for updating the status of tasks.

6. Discussion

6.1. Usability, limitations and benefits

The case study explores possibilities into the digital twinning of a time and space-constrained construction process. Access was granted to researchers in a period of time in which predominantly, the construction followed the erection of a casted on site RC 9 floors module. The selection of the information pipelines was influenced and limited by these constraints. As a result, the focus of this case study was on structural analysis control and supply chain of structural materials. Two keys usability aspects are worth pointing out.

- During this period, data collection at the site involved sensors and laser scanners, processed by custom applications to provide decision-ready analysis to end users. This included monitoring structural materials and their supply chain. Repetitive tasks were identified. Every three weeks, one floor was added to the module. A timely update on the information every week was found useful for enabling timely managerial improvements. The case study shed light for the application of this approach on sequential erection of RC frames.
- This approach, applied across various construction stages, would allow for the development of additional information pipelines related to other aspects of construction. Such pipelines would also involve data collection, data processing by applications, and insightful decision-making based on measured information analysis. Crucial considerations involve the temporal relevance of collected data and recognizing patterns in repetitive tasks to enhance subsequent construction phases.

Fig. 25 illustrates the usability of the developed DT in a generic way. It is based on the identification of information pipelines during specific repetitive tasks that are held at different construction stages. All these pipelines provide information that is processed by custom applications (openness to modularity of such applications is key). Subsequently, processed information can be visualized by managers and weighed accordingly for assessing both specific actions but also, for the aggregation of all actions in broader key performance indicators.

More generally, data-collection on construction sites offers significant benefits by providing decision-makers with access to data-informed insights. Accurate and up-to-date data provide to project managers with better ideas to make informed decisions, identify potential issues early, and optimize project performance. In addition, collecting data from multiple sources can provide a comprehensive view of the construction site, enabling the aggregation of data for analysis by different stakeholders. This can help contractors, architects, and other parties involved in the project gain a better understanding of the site's status, progress, and performance. A digi-

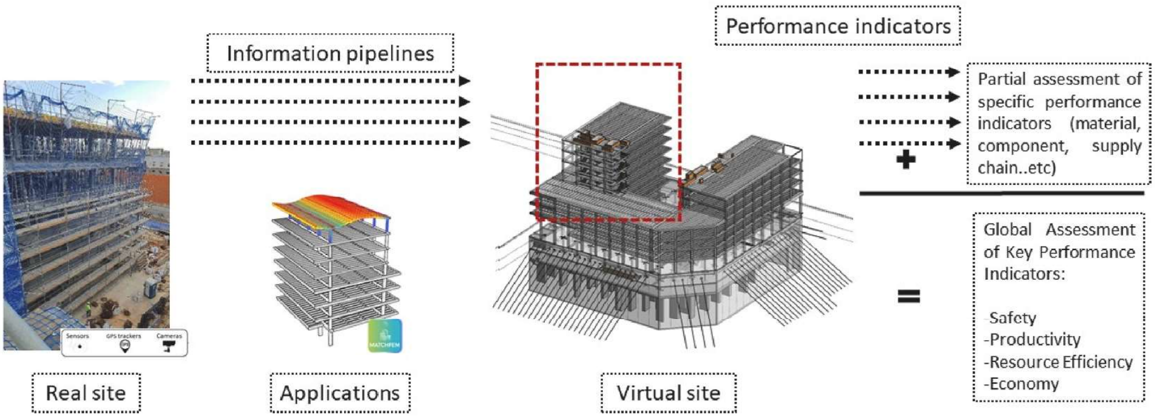

Fig. 25. General perspective of the usability of the Digital Twin.

tal twin conceived for many sources of data is ideal as a recipient of information provided by many stakeholders. Adequate versatility of information pipelines in terms of connection with various sources is key. In construction sites, due to the variety of tasks involved, the only way all stakeholders benefit/contribute from/to a DT is with interoperable frameworks.

6.2. Challenges and bottlenecks for DT-enabled data-collection on sites

Logistics can pose a significant challenge for data-collection on construction sites. Remote locations, difficult terrain, collisions between tasks and task crews, delays, limited access to skilled workers or to technologies or limited access to sites are only few of the potential bottlenecks one may find. Digitization has not reached market maturity which means that it will take several years to be a priority. This limits the necessary resource allocation to activate equipment and personnel to collect the necessary data at the right time. Privacy is another critical bottleneck. Data-collection on construction sites often involves capturing sensitive information about workers, equipment, and processes. Ensuring that this data is handled securely and in compliance with relevant privacy regulations can be a significant challenge. Not collecting data is often easier to handle than its counterpart. Stringent time constraints are also a significant factor that can limit the effectiveness of data-collection efforts on construction sites. Presently, good quality data requires specialized crews regularly present on site. With tight project timelines, data-collection must be carefully planned to avoid disrupting construction activities or most often, to avoid missing vital data. Data must be collected timely, quickly and accurately to ensure that it can be used to make informed decisions about the project's progress and status. The development and implementation of several pipelines of information within the same building construction shows the varied nature of information sources. This variety illustrates many of the bottlenecks and challenges such digitization crews may experience. Specific observations related to benefits, challenges, bottlenecks and potential improvements of these strategies are identified. Table 4 summarizes key takeaways extracted from the developments of the information pipelines depicted in section 5.

6.3. Lessons learned with construction managers

Access to the site was enabled by those stakeholders in charge of supervision of structure quality control. Even though construction managers were daily informed about actions, communication between the research team and other stakeholders was limited. The gathered feedback comes from presentations and summaries that were provided to the incumbent stakeholders after developing the described actions. It is worth mentioning again that this case study involved private sector only stakeholders. Feedback from collaborators can be summarized with the following key takeaways.

- The level of technology readiness during this particular study has not permitted timely actions for decision making. The case study has provided a realistic ground to implement information pipelines but it has not permitted to act weekly using conclusions from the extracted information. During the development of the actions, the construction of the building continued its pace. Stakeholders acknowledged that more mature technology readiness would be key. Technology readiness is desired for potential

Table 4
Use of results, bottlenecks and potential improvement at the site.

Name	Benefits during construction	Bottlenecks and challenges
PCL	The proposed pipeline helps to identify potential sources of inefficiency in repetitive tasks using discrete event simulators. By using data-driven DES, friction between steps of the sequences can also be detected. For instance, the delivery period of upcoming concrete truck supplies can be adjusted or different construction activities to reduce congestions or idle times.	Accurate results are obtained when data is collected and analyzed continuously. One challenge is to automate the data-collection and treatment for the end-user without the need of intermediate adjustment of models.
LS	The proposed information pipeline helps to control post-tensioning activities. Information about stress-states of the slab after tensioning is of great interest for structural engineering managers. By updating DT with such measurements, numerical models can be verified with data from the sites. Subsequent analyses can be based on more realistic conditions. Excessive (or too little) tensioning can be detrimental for the performance of the structure.	Using high precision equipment at the construction site is a delicate task. Sensors and measurements are fragile and require careful implementation. Integration with structural analysis models depends on the interoperability between tools
SD	The proposed information pipeline allows obtaining detailed information about the deflection of the slabs and execution times during the erection process of the building. Including these measurements in the normal erection workflow provide a continuous quality control of the erection process and the structural performance of the slabs.	Stakeholders implementing laser scanner measurements in sites need to have knowledge of point cloud processing. Scan-to-BIM procedures are still under development and their use has not reached maturity in the market.
CM	The proposed information pipeline allows to update nonlinear and time-dependent structural models with concrete maturity monitoring data from the construction site. Beneficial effects may include decisions on data-informed formworks removal or accelerated construction	All concrete batches with different mixes require calibration. Laboratory tests are required for this purpose (for every mix used in the site).
AV	The proposed information pipeline allows to get insight of the column vibration process. The implementation of this framework has the potential to improve quality monitoring of the columns and energy control of the process.	The task is straightforward to complete on site but signal analysis requires careful inspection. The optimal vibration time depends on many factors and structural types. The challenge is to apply the procedure in identical repetitive elements.
CPM	The proposed pipeline supports the identification of delayed activities according to the project's construction schedule, enabling response actions to accelerate processes. As a result, an improvement in productivity and performance is achieved, reducing time and costs.	The effectiveness of the construction progress monitoring pipeline depends on the commitment of the construction manager or technical assistant to perform constant visual inspections to update the status of the tasks on the mobile app.

technology adoption as in other industries but, to achieve technology readiness, research is needed. Mid-to long-term benefits are expected in such case.
- Usefulness and revenues are the main target once implementation is solved. However, managers were skeptical about how information can be synchronized with so many actors involved in a construction site. Evidence found in this particular case study shows that if managers want to make use of and leverage information weekly, many players need to update digital info timely. It would presume clear conditions established with sub-contractors beforehand.
- After technological advances, usefulness and monetization become clearer, it is expected that contracts, conditions and bids will be established in a way digital information is requested systematically. In Spain, BIM adoption is accelerating since for projects of a certain size, it has become mandatory. Lively versions of BIM such as digital twins provide evidence for fine tuning such expectations.

7. Conclusions

Digital twins (DT) of infrastructure systems represent tools that are capable of playing useful roles in assisting the design, construction, and maintenance of complex projects. In particular, great interest for DT occurs when they prove crucial in increasing productivity, safety, resource efficiency and economic benefits during construction. To date, universal implementation of DT in construction sites is its infancy. The nature of construction sites with many stakeholders as well as many different tasks occurring simultaneously represent the biggest bottleneck for this comprehensive implementation. All stakeholders in construction sites usually represent specific tasks which usually represent a specific information pipeline. In this study, information pipelines are abstracted as the flow between data-collection, analysis and decision-making process based on the results. Recognizably, to ensure their success, these DT must be sufficiently open to allocate this variety of stakeholders. If one understands the variety of tasks as a challenge, the contribution of many pipelines add information to a vaster entity of great interest for construction managers. All pipelines contributing to the DT must be able to plug and play to centralized systems and dashboards in a relatively easy way to ensure its use and to avoid friction in the system.

The case study highlights the importance of several pipelines of information that range from data-collection to performance indicators, and it describes six pipelines of information in detail. All pipelines are independent one to another, use different collected data and use different tools for analysis. As a matter of fact, these pipelines also represent six potential stakeholders that independently contribute to the same DT.

The proposed framework for a dashboard seeks to enable a centralized end-user application addressed to construction managers. Different sources of information can be visualized together at the right time. A timely use of this information opens manifold possibilities for a timely analysis of the construction process. During this process, managers can suggest data gathering from many perspectives according to the construction site singularities. As a result, the specific monitoring of one site becomes tailor-made with a potential of improvement of the process at the right time.

The case study identifies both the benefits and bottlenecks of digital twins on the construction site. While digital twins provide a wealth of data that can improve decision-making, they also require significant investment and expertise. However, potential improvements can be made to address these bottlenecks, including improving the quality and availability of data, and enhancing collaboration between project teams.

Author statement

R.C, H.P: study conception and design. H.P, M.J., C.R, R.T., T.H. and R.K: data collection, analysis and interpretation of results. Manuscript preparation: R.C, H.P, M.J., C.R. and R.K. Manuscript edition and supervision: R.T., T.H.

Declaration of competing interest

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

Data availability

The authors do not have permission to share data.

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