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A General Contractor's Perspective on Construction Digital Twin: Implementation, Impacts and Challenges

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Abstract: The Digital Twin (DT), as a real-time and data-connected virtual replica of a physical asset, introduces a new paradigm in the construction industry. To date, the use of DT in the construction phase has not been addressed sufficiently. Hence, this research studies the implementation of DT during the construction phase of projects to support general contractors' decisions and operations. Starting from existing literature, a Construction Digital Twin (CDT) framework has been developed from a general contractor's perspective and a case study was implemented as an application of the proposed CDT to validate the framework and demonstrate its benefits. In the selected project, the simulation of the construction operations in evaluating various "what-if" scenarios for optimum resource allocation and operation management proved the benefits of using a CDT in the construction phase of projects for general contractors. By implementing the proposed CDT framework, several impacts such as reduced costs, improved collaboration and information exchange and data-driven construction management can be anticipated.

Keywords: BIM; construction digital twin; construction phase; data-driven construction; general contractor

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1. Introduction

Although the ample benefits of Industry 4.0 have been proven, and industries such as automotive manufacturing and maintenance are focusing on the interaction between industry elements and IoT devices, the construction industry is lagging in the implementation of Industry 4.0 technologies such as Digital Twin (DT) [1,2]. In the embracing of Industry 4.0 concepts, Construction 4.0 initially relied on the extensive application of Building Information Modeling (BIM) in different stages of the product/asset lifecycle, while subsequently focusing on different areas of innovation such as industrial modular production, cyber-physical systems (CPS), supply chain and construction site works monitoring and data analytics including big data, Artificial Intelligence (AI), cloud computing and blockchain [3,4]. In addition to BIM, Digital Twin (DT), as one of the main concepts of Industry 4.0 and a subset of a CPS, bespeaks a new paradigm in the construction industry as a real-time virtual replica of a physical asset.

Construction companies are seeking to adopt new technologies to increase their profits and add value for their customers. Particularly in a context where construction project complexity is growing and coupled with the need for higher productivity, innovative solutions for tackling such challenges, such as Industry 4.0 technologies, are in demand [4]. Hence, a general contractor can benefit from a Construction Digital Twin (CDT) during its construction activities to increase its profits, decrease risks and also increase its customer satisfaction at the delivery and hand-over stage.

Considering the industry demands, as a possible solution the novelty of this study lies in developing and proposing a CDT framework to support the decisions of a general contractor during the construction activities of a project. A constructive research methodology was used to develop and validate the proposed CDT framework.

More details on DT and its uses in the construction industry are discussed in Sections 1.1–1.4. Then, in Section 2, the research methodology for conducting this study is described. Next, in Section 3, the developed CDT framework along with its components are presented. Then, in Section 4, a soil management case study implementation demonstrates the application of the proposed CDT framework to address a real-world issue in construction sites. Finally, this study concludes with a discussion about the impacts and challenges/lessons learned of the CDT in the construction industry.

1.1. Digital Twin—An Industry 4.0 Concept

Industry 4.0 is a collective term for a number of building blocks consisting of Internet of Things (IoT), Big Data, Cloud Computing, the Internet of Services, Cyber-Physical System (CPS), Smart Factories, Advanced Manufacturing, Digital Twin, etc. [5–7]. The essential building blocks of Industry 4.0 are cyber-physical systems (CPS) that link the digital and physical worlds through networks and computational resources [2,7].

As a specific form of a CPS, Digital Twin aims to provide a digital replica of the physical product or process in real time or near real time and capture all useful information throughout the product or process's lifecycle [6,8]. Serving as the virtual and computerized counterpart of a physical system, DT enables the simulation and real-time synchronization of the sensed data from the field acquired via enabling technologies of Industry 4.0 such as IoT [5].

1.2. Digital Twin Definitions

Grieves and NASA provided the first definitions of Digital Twin. Although there is no universally accepted definition of Digital Twin due to different viewpoints, researchers and institutions have provided broader definitions of Digital Twin [6,9]. Table 1 provides various definitions provided in the literature with respect to their associated industry.

Table 1. Definitions of Digital Twin in various industries.

Reference	Definition	Industry
Glaessgen and Stargel [10]	A Digital Twin is an integrated multi-physics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.	Aeronautics
Negri et al. [5]	the virtual and computerized counterpart of a physical system that can be used to simulate it for various purposes, exploiting a real-time synchronization of the sensed data coming from the field.	Manufacturing
Hasan et al. [2]	a representation of a physical entity via a virtual model that mimics its change in state whether it is mechanical motion or physical/dimensional changes.	Construction
Xu et al. [11]	a comprehensive virtual copy of the physical operating facility throughout its complete lifecycle—starting from idea and up to decommissioning and project closure.	Construction
LaGrange [12]	advanced 3D models, representing dynamic, cross-domain digital models that mirror the performance and operation of a physical asset or process as it moves through the lifecycle—from design, engineering, construction, commissioning, and finally, into operation.	Oil and Gas
Khajavi et al. [13]	The digital counterpart of a physical asset designed to integrate real-time sensor readings to analyse and improve asset's operational efficiency and interaction with the environment and users, and to enable predictive maintenance.	Construction
National Infrastructure Commission [14]	A digital twin is a virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning and reasoning.	Infrastructure
Madni et al. [15]	A digital twin is a dynamic virtual representation of a physical system that is continually updated with its physical twin's performance, maintenance, and health status data throughout its life cycle.	Systems Engineering
Jones et al. [16]	a system that couples physical entities to virtual counterparts, leveraging the benefits of both the virtual and physical environments to the benefit of the entire system.	Manufacturing

Table 1. *Cont.*

Reference	Definition	Industry
Bolton et al. [17]	a realistic digital representation of assets, processes or systems in the built or natural environment.	Built Environment
Pan and Zhang [18]	a mirror and digital depiction of the actual production process, which can imitate all aspects of physical processes under the integration of physical products, virtual products, and relevant connection data.	Construction
B.I.M. Dictionary [19]	A set of digital assets—models, documents and datasets—that mirror a physical Asset for part/whole of the Asset Life Cycle.	Built Environment
Grieves [20]	a virtual, digital equivalent to a physical product . . . [and] rich representations of products that are virtually indistinguishable from their physical counterparts.	Manufacturing
Boje et al. [21]	the digital representation of the building, enriched by the addition of sensing capabilities, big data and the Internet of Things from site to building operation.	Construction
Barricelli et al. [22]	A DT is a living, intelligent and evolving model, being the virtual counterpart of a physical entity or process.	General
Grieves and Vickers [23]	the Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level.	Manufacturing

A close look at the provided definitions leads to the understanding that, regardless of the industry type, a DT is basically composed of a physical entity, a virtual entity that represents its respective physical peer and a data link to couple these two to capture the status of the physical entity. Moreover, the various definitions provided in Table 1 imply the spread of the DT in different industries, including construction and the built environment.

1.3. Digital Twin in the Construction Industry

Increased interest in the Digital Twin has encouraged the construction industry to follow this concept. However, in the AEC/FM industry, the DT has not been defined comprehensively by both academia and practitioners, and it is often confused with BIM models for design, construction and operation/maintenance [9,12,24]. Unlike BIM, which reflects the states of a project in a static manner, Digital Twin is dynamic and holds a bi-directional connection with the physical asset and captures its status in real time or near real time.

In the construction industry, improving productivity, sustainability, safety and achieving other organization or project goals are the key purposes of a DT [25]. Infrastructures, the built environment and city assets can benefit from the applications of DT in monitoring, managing and predicting an asset's current and future status. For instance, Pan and Zhang [18] proposed a Digital Twin framework integrating BIM, IoT and data mining techniques for a more efficient project management. Lu et al. [1] presented a system architecture to implement the DT at building and city levels, focusing on Facility Management (FM). Ham and Kim [26] worked on the DT at the city level by proposing a method for leveraging unstructured crowdsourced visual data for locating objects in urban areas that are vulnerable and have potential risks for citizens. A number of researchers conducted studies in the area of the DT in the construction industry [2,4,27–32] and, as Boje et al. [21] and Wanasinghe et al. [9] revealed, using DT in various industries, especially the construction industry, has gained momentum in the recent years.

1.4. Digital Twin in the Construction Phase: Construction Digital Twin (CDT)

In the product manufacturing stage, DT can realize real-time product monitoring and accurately predict performance. In addition, with the utilization of DT, the consistency of the final product with the required specifications can be evaluated at this stage [33]. In this sense, the building products constructed, fabricated and installed by the general contractor can be monitored and checked against the required performance level by using a DT. Having said that, the DT can verify or predict the effective performance of the building component in real time, which can be the basis for quality check assessments and, subsequently, payments to the general contractor. Monitoring the building components, workers and construction equipment is a challenge during the construction phase. Therefore, the DT approach for the construction stage can often be highly desirable since it enables actionable knowledge and effective decision making in the construction phase based on real-time data and measured productivity and performing “what-if” scenarios, which in turn reduces the construction waste (in the broad sense of time, effort, materials) to a great extent [3,9,12,34].

Although the design and construction phases of a project account for a considerable portion of the total project’s cost (up to 40 percent), most construction industry studies and practices have focused on the implementation of the DT in the operation and maintenance phase of facilities [35] and the level of DT development during construction is still very low [21]. Considering the substantial impact of the design and construction processes of an asset on its operation costs [21], any benefit from the DT during construction will have added value. In addition, the gathered data from the current monitoring technologies (e.g., range finders, laser scanning, GPS, RFID, Wi-Fi, UWB, smart sensors, etc.) in the construction industry are generally used in an isolated fashion with a single-subject focus where there are very few cases of the integrated use of more than one technology [3]. There is also a lack of clarity on the potential technologies for higher levels of CDT in terms of integration with socio-technical platforms and using simulation, optimization, learning and end-user engagement, mainly due to a lack of implementation and research at such levels of sophistication [21].

Sacks et al. [3] focus on developing a Digital Twin Construction workflow for the design and construction processes of a product. Depending on the nature of the contract and the project delivery system (Design Bid Build, Design Build, etc.), a general contractor might or might not be engaged with the design process. In addition, in many processes, such as construction supply management and construction equipment management, the general contractor intends to control and improve its internal processes rather than having a comparison between the as-design and as-built statuses. They present a conceptual workflow for the planning and control of the design and construction processes using Digital Twin information systems while leaving the researchers/practitioners without solid practices in the design or construction process. Their emphasis on the impossibility of having a closed loop model of construction control prior to the new enabling technologies is not valid in the real construction practice. They define Plan, Do, Check and Act cycles as the structure to achieve a closed loop production control. Either manually or automatically, by any technology, if not all for most construction processes, monitoring, comparing current and designed/planned status and acting accordingly is a routine project control practice.

Essential to the execution of a process or producing a product in construction, a flow of information including material, labor and equipment information is needed. Capturing the information flow about the product and process and considering their constraints on a specific time basis, which is determined by the project specifications, nature of the product/process, etc., would enable actionable decisions. Despite the existing literature that focuses on a single stream of information (material, or labor, or equipment), as depicted in the case study, the CDT framework developed in this research requires the acquisition of all the necessary information of the product or process through the deployment and integration of the enabling technologies.

Therefore, considering the existing gaps, this study is motivated by deriving a Construction Digital Twin (CDT) framework from the existing literature and develop it from a general contractor’s perspective to implement DT in the construction phase of projects. In addition, this study demonstrates the CDT’s potential in using more than one monitoring technology, as well as using higher-level technologies such as simulation in implementing a DT during the construction phase, as shown through a real industry case. The case study demonstrates the practicality of the proposed CDT framework in areas that the general contractor can benefit from.

2. Research Methodology

This study benefits from a constructive approach for its research methodology, elaborating the CDT framework against the objective of supporting general contractors' actions for DT implementation in construction sites. An extensive literature review from various industries was performed to derive and elaborate the developed CDT framework from the existing theories. Building Information Modeling and DT implementation, along with their principles and features, data analytics and simulation technique, were performed in the form of a case study conducted in a construction project to calibrate and validate the proposed CDT framework. A coherent and feasible Construction Digital Twin (CDT) framework and workflow for information management throughout the construction phase is developed. The defined conceptual schema of the Construction Digital Twin identifies for each component—the virtual model, the data collection systems on-site, the connecting infrastructure—their requirements, their functioning and the potential available solutions, also taking into account the necessities of each discipline. Predictive algorithms and data analytics to exploit the data and the information stored in the Digital Twin are explored. The enabling technologies for data collection in a construction site are discussed. One simulated case study in the field of civil projects is discussed to demonstrate the potential implementation of the Digital Twin approach. In this case study, the Digital Twin solutions and data collection equipment along with their specific Information Delivery Specification (IDS) are explained and modalities of predicting construction evolution and reporting to the project management team are defined. To conclude, this study discusses and assesses potentialities and limits regarding Digital Twin implementation in the construction industry, providing perspectives and requirements for further developments in the field.

In the remainder of this study, the Construction Digital Twin (CDT) framework is introduced along with its components. Next, an application of the CDT is demonstrated as a case study. Finally, in the discussion section, the impacts and challenges of the proposed CDT framework are evaluated.

3. Construction Digital Twin (CDT)—A Framework for a General Contractor

A CDT of a physical entity starts its life before or during the construction phase. In other words, the focus of a CDT is on the pre-construction and construction phases of a project or physical entity. As BIM models are not continuously updated, and have limitations in real-time data synchronization and model updating, a CDT fills this gap by integrating the physical entities, virtual models, analytics and prediction capabilities and services by real-time or near real-time data connections during the construction phase. This feature of the CDT enables concurrent monitoring, data analysis and prediction capabilities.

Considering the literature review from various domains and the current research landscape, this section proposes a CDT framework for DT deployment during the construction phase of projects, allowing contractors to take advantage of the DT and its uses during the construction phase. Lu et al. [1] propose a system architecture for the DT at a city and building level. They break down the DT architecture to the composing components for operation and maintenance purposes. A similar concept was followed by this study to develop the structure of the CDT framework based on the composing tiers. Through the investigation of the DT in various industries (e.g., manufacturing, systems engineering, infrastructure, oil and gas, construction, etc.) and applications (e.g., production, planning, facility management, safety, etc.) (see, e.g., [2,11,12,15,16]), the core components of the CDT framework along with their respective syntax were introduced. Table 2 presents the DT components introduced in a handful of the reviewed studies and provides hints for the implementation of the proposed frameworks in the construction phase from a general contractor's point of view.

Table 2. The DT components in some of the reviewed studies and their relevance to construction phase.

Reference	Digital Twin Components	General Contractors' Viewpoint
Glaessgen and Stargel [10]	As-built configuration model, monitoring and measurement, virtual model, prediction, integrating data, mirroring the actual flight, anomaly detection	Modifications needed to be tailored for construction phase
Negri et al. [5]	-	Focuses on manufacturing systems; a framework for DT implementation is not presented
Hasan et al. [2]	Physical model, digital-physical link, digital interface	Suitable for interaction of construction machineryNot generalized to construction phase; limitations in analytics and predictions, single application
Xu et al. [11]	Real object, data, connection, analytics, Digital Twin	There is not a clear framework to implement DT in construction phase; lack of real case study
LaGrange [12]	Equipment and plant twin, process twin, data and workflow, performance twin, OEM services	More focused on maintenance and operation of facility/asset, operator training, etc.; lack of construction phase examples; lack of tools and enabling technologies of each component
Khajavi et al. [13]	Required data components from BIM, wireless sensor network, data integration and analytics	Focused on the operation phase of the buildings
National Infrastructure Commission [14]	-	A DT framework in not presented
Madni et al. [15]	Digital Twin, physical twin, data, connection, data acquisition and other tools, etc.	Focusing on operation and maintenance; lack of a clear framework for implementation
Jones et al. [16]	Physical entity, virtual entity, physical environment, virtual environment, state, etc.	Provides a literature review of DT; terminologies/frameworks do not provide insights/explanations for a general contractor or construction phase
Bolton et al. [17]	-	Focuses on the principles in a broad view, not on a specific entity or phase
Pan and Zhang [18]	Physical model, data collection, mapping, data mining, virtual model, decision making	The presented framework focuses on the use of data mining techniques for bottleneck detection and progress prediction; it does not generalize the framework for the vast variety of construction works or present the components/enabling technologies for them
B.I.M. Dictionary [19]	-	-
Grieves [20]	Physical space, virtual space, connections of data and information between two spaces	Presents a general framework but not detailed enough to be implemented by a general contractor; the focus is on manufacturing factory products
Boje et al. [21]	The virtual part, the physical part, the data connection	Lack of practical case examples to demonstrate the implementation of Construction Digital Twin by contractor in construction phase
Barricelli et al. [22]	Connection and data exchange, data storage, ontologies, data analysis/ML/AI techniques, self-adaptation and self-parametrization	Elaborates on definitions, characteristics and applications of DT but does not provide a framework for implementation of a DT
Grieves and Vickers [23]	Real space, virtual space, the link for data and information flow between real space and virtual space	A framework is not presented for the implementation of a DT

Next, taking into account the inputs and outputs of each component group and the logical order of implementing a Digital Twin, a structured framework was organized resulting in a seven-tier framework. Accordingly, the general processes of the construction phase and their information flow with their respective products, sequence and requirements from a contractor's point of view were integrated with the previous step to revise and enrich the framework by adding necessary components and information flows to make the framework more compatible for use by general contractors. Then, the developed CDT framework was calibrated and validated by implementing a real-world problem in the context of a construction project. The proposed three-dimensional DT in the literature, i.e., the Physical, the Virtual and the Link [23], is expanded in this study by adding three more components, namely data, prediction and analytics and applications to properly serve the purpose of a CDT in terms of ingesting required data, analyzing and predicting product evolution and providing services Figure 1 depicts the CDT framework and its main tiers, their related enabling technologies for CDT implementation and the information flow between them.

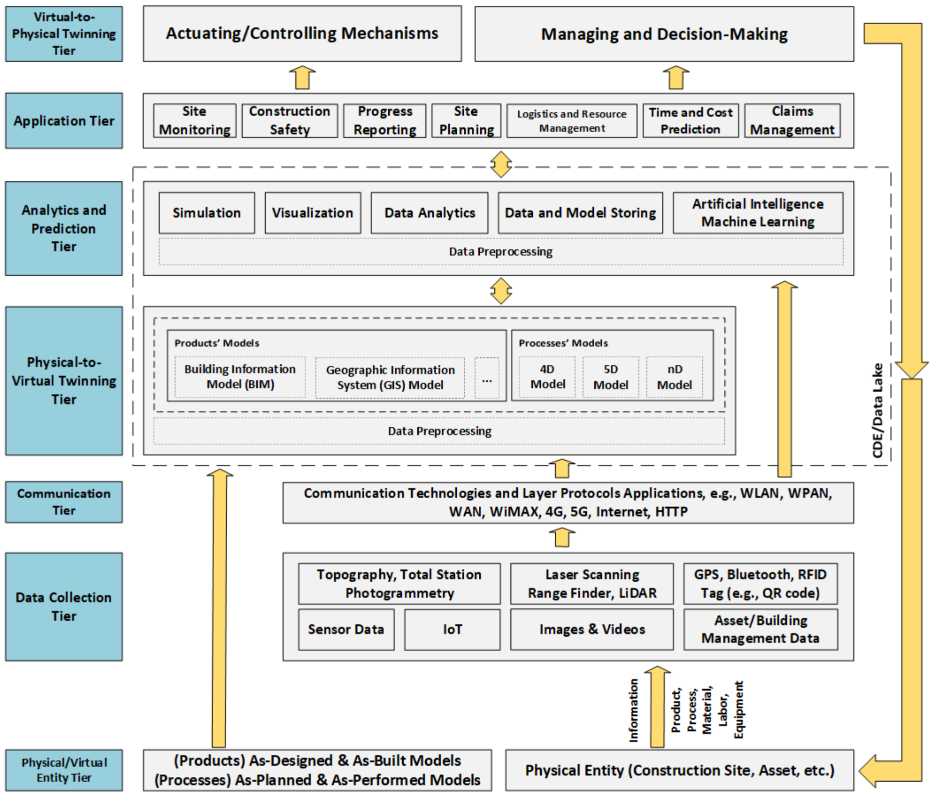

Figure 1. The Construction Digital Twin (CDT) framework for general contractors, including its tiers and enabling technologies examples.

The developed CDT framework consisted of seven tiers: the physical/virtual entity tier, data collection tier, communication tier, physical-to-virtual twinning tier, analytics and prediction tier, application tier and virtual-to-physical twinning tier. Each tier has its specific components and enabling technologies to serve its required purposes, e.g., gathering data, disseminating data, analyzing data, updating the virtual environment, acting on physical entities, etc. In addition, the CDT framework demonstrates the sequence of each tier and the data/information exchange between them.

In the coming paragraphs, each tier is explained. Next, a soil management case study as the application of a CDT is implemented via the proposed framework to validate its applicability and effectiveness and detect the barriers of implementing such applications using the proposed CDT framework.

3.1. Physical/Virtual Entity Tier

The first step in establishing a CDT is identifying the desired physical objects that the CDT would replicate and developing their digital models, i.e., product or process models. This tier represents the existing physical object and the virtual entity created through digital modeling. Modeling is the basis of implementing a DT in practice [36]. Digital modeling in the physical/virtual entity tier is a collective term for the various digital models of products or processes representing physical reality. Building Information Modeling models are examples of digital modeling for various disciplines such as architecture, structure, site, etc. The existing models that depict the reality of the physical entity (e.g., as-built

BIM models, etc.) can be adopted, or new models can be developed. These models are fundamental elements of the CDT framework.

3.2. Data Collection Tier

Considering the philosophy of a DT to gather data in real time and update the virtual model of a physical component, collecting data is a vital part of a DT. Based on the scope and focus of a specific DT/CDT, data collection aims to gather data from particular physical entities, such as construction elements/components, building systems/sub-systems, construction resources (materials, equipment, manpower), etc. For this purpose, there are a range of technologies available for data gathering, e.g., smart sensors, IoT devices, RFIDs, GPS, photogrammetry and laser scanners, etc., each of which has its specific data type and format and acquisition method. However, due to the complex nature of construction projects and the specific configuration and purpose of a CDT, finding a suitable tool for data collection may be challenging.

3.3. Communication Tier

A secure, reliable and high-speed network is required for real-time or near real-time data exchange in a DT [25]. The locally gathered data need to be transmitted to upper layers to update the digital model based on the current status of the physical entity. The data are also used for analysis and visualization purposes. This communication infrastructure can adopt a wide range of technologies such as WAN, WLAN, 4G/5G, Bluetooth, ZigBee, GSM, LTE-M, etc., as communication and wireless technologies and HTTP, MQTT, mDNS, DDS, CoAP, AMQP, XMPP, etc., as layer protocol applications [1,37]. Each data transmission technology has its specific capabilities and limitations. Security measures must be considered in developing a DT/CDT as gathering and transmitting data are suspect to hacking and viruses, especially when dealing with private, confidential and valuable information [22].

3.4. Physical-to-Virtual Twinning Tier

A Digital Twin is conceived as a living and evolving model that is connected to its physical twin and provides a concurrent and up-to-date representation of the physical twin and its key processes and features [3]. In the physical-to-virtual twining tier, the captured status of the physical twin is reflected in the virtual environment and the virtual twin is updated accordingly. The twinning process is bonded with continuous interaction, communication and synchronization between the virtual twin and its physical twin as well as the surrounding environment by continuous and real-time information exchange [22]. The twinning process occurs within a frequency called the twinning rate [16]. Depending on the work topologies and requirements of the CDT for a specific application, the twinning rate can be of different time spans. The real-time updating, i.e., high twinning rate, enables the DT to be constantly aware of what is happening in the physical world [22]. Therefore, this tier aims to continuously update the as-built/as-is and as-performed condition of the physical twin; hence, they can be the basis for comparisons with as-designed and as-planned models.

3.5. Analytics and Prediction Tier

The analytics and prediction tier contains the required functions for data processing, data analytics, simulation, data storing and visualization, AI, Machine Learning (ML), etc., to analyze data and perform predictions, simulations, etc., based on the real-time gathered data. This tier feeds the upper tiers and supports them in decision-making and actuating mechanisms (e.g., sounding an alarm, closing/opening or turning an element on/off, etc.). The collected historical data stored within the virtual environment can be reused for future virtual processes. This capability enables the Digital Twin to learn from its past [16]. Managing raw data coming from different sources and generating valuable insights and knowledge will support improvements and optimizations in processes. It also enables the development of new data-driven services and applications that eventually contribute to predictability and real-time or near real-time reactivity [38]. Data analytics, visualization techniques, machine learning, data mining, etc., can be deployed for knowledge discovery and insight extraction to assist relevant stakeholders. Alternatively, simulation techniques can be deployed to evaluate various "what-if" scenarios about the real-world system. Consequently, the simulation results can be deployed for project scheduling, construction equipment management, construction site safety and other important practices needed for successful project delivery.

3.6. Application Tier

The application tier in the CDT framework interprets or visualizes the project status and triggers a decision-making action or an actuating function. Being fed by physical-to-virtual twinning and analytics and prediction tiers, this tier can provide various services such as site monitoring, site planning, claims management, etc., to the general contractor throughout the construction phase. Based on the scope and focus of a CDT, the expected outputs are different, e.g., selecting the optimum amount of equipment needed to perform construction activities, monitoring the desired construction entities, procurement and foreseeing the supply needed for the upfront construction activities, etc. However, a group of CDTs with different purposes could be connected to work as a CDT system.

3.7. Virtual-to-Physical Twinning Tier

Being fed by the application tier, the virtual-to-physical twinning tier is the top tier in the CDT architecture that applies the decisions to the physical twin or actuates predefined mechanisms, i.e., feedback from cyberspace to physical space. The output of this tier directly influences the physical twin that completes the closed-loop control system. Therefore, the information flow from the virtual to physical entity happens in this tier, i.e., virtual-to-physical twinning, and it completes the bi-directional communication between the virtual and physical twins. In this tier, the virtual acts on the physical and changes its status based on the specific application (monitoring the construction entity, managing construction equipment, site safety practices, etc.), data analytics and prediction outputs and updated models. This tier can trigger an automatic/control mechanism or assist relevant entities with managing and decision making. Depending on the available technology and the desired application, a level of human intervention might be engaged in this tier. As an example, an excavator Digital Twin can be used for operation control and monitoring. The bi-directional data connection enables the end-user to run the equipment remotely or provide a decentralized platform for collaboration. A tablet with an augmented model of the excavator can also be used to transfer the changes made by an augmented model to the physical entity [25]. In the next loop, the virtual catches the new changes in the physical and updates its status accordingly and through data analytics and acting on the physical twin the next loop is completed. Each loop occurs according to the twinning rate that has a direct relation to the requirements of the desired application of the CDT.

4. Construction Digital Twin Applications—A Soil Management Case Study

This section introduces the practical uses of a CDT to unveil its potential benefits in managing real-world problems in the construction phase of projects. Initially, three practical case studies were considered for implementation via the proposed CDT framework. These cases were construction soil management, safety in the deep excavations of retaining walls and supply management for high-volume concrete pouring tasks. Due to resource limitations and case importance, the soil management case study was implemented using the developed CDT framework to validate its applicability and effectiveness and to detect the barriers to conducting such applications using the proposed CDT framework.

One of the main issues in each construction site is managing the soil produced during the construction phase. From the project's commencement, earthwork operations usually exist up to the end of the construction phase, making it not a temporary short-term process but rather a long-term process that requires proper management and time-to-time monitoring. An assessment of the construction projects of 10 industrial buildings showed that the average cost of earthwork operations, including excavating, backfilling, loading, transferring and unloading soil (excluding supply), equals 8 percent of the total contract sum. Moreover, in projects such as road projects earthwork operations consist mostly of the contract amounts.

Depending on the type of project, i.e., building, road and infrastructure, power plant, oil and gas, etc., a variety of sub-contractors might be present at a construction site and work simultaneously. Depending on the subject and scope of their contracts, they might produce extra soil, need soil, or both to perform their activities. As they are working under the umbrella of a general contractor, the general contractor needs to manage the soil in terms of defining its optimal location (inside or outside the construction site), monitoring its status on a timely basis, predicting necessary volumes for front and upcoming activities, managing earthwork machinery (e.g., trucks, excavators, etc.), transferring the soil from the temporary location to the permanent location to abide within urban and environmental rules and other related issues. These issues can impact the final expenses of the general contractor and the time, cost, quality and safety of the project.

Another challenge is that a general contractor may encounter claims from its sub-contractors regarding soil and its various aspects, such as soil supply. As earthwork operation cost is a considerable portion of the contract sum, improper soil management can lead to considerable expenses and non-compensable project cost overruns that the general contractor must shoulder. On the other hand, efficient soil management can help prevent such claims and facilitate the ongoing or upcoming activities that need soil deposit/borrow.

In the following Sections 4.1–4.7, the case study of soil management is implemented step by step based on the developed CDT framework to expand the knowledge of using Digital Twins during the construction phase of projects and assist general contractors and practitioners in managing different aspects of their projects. This case study serves the CDT framework, as the core of this study, by going into details and expanding Section 3.

4.1. Physical/Virtual Entity Tier

Since a DT is meant to be a reliable virtual replica of a physical reality, a high-fidelity virtual model is essential in developing any DT. Fidelity levels (i.e., low, medium, or high) demonstrate how closely aligned the virtual and physical twins are. Hence, in this case study, care was taken to develop a high-fidelity digital model with all necessary aspects regarding the management of the soil in terms of cut/fill volumes, location of the construction site, location of the soil deposit/borrow, access routes and distance from the construction site to the soil deposit/borrow location. The case study for demonstrating the CDT application for soil management was a hospital project in Milan, Italy.

In this CDT application, the physical component virtually replicated is the soil deposit/borrow, which functions as a source of soil supply for fills and a dumping point for extra soil from cuttings/excavations. This component has a specific location inside or outside the construction site. Another important feature of the soil deposit/borrow is its volume, which is monitored and calculated in each twinning cycle to inform the decision makers about its current status. Once this as-built or as-is model is created, it is continuously updated in the "physical-to-virtual twinning" tier as data are acquired from the construction site and the physical entity.

The other physical component in this CDT is the construction site. As the earthwork operations progress, the site model can be updated and the volume of the performed excavation and remaining excavation can be calculated. This can also be used to compare the actual earthwork operation progress with the planned progress in the project schedule to see whether the earthwork activities are ahead of or behind the project's schedule. In this CDT application, the soil deposit/borrow was the physical entity and the construction site was only considered to reflect the location and its distance from the soil deposit/borrow (see Figure 2).

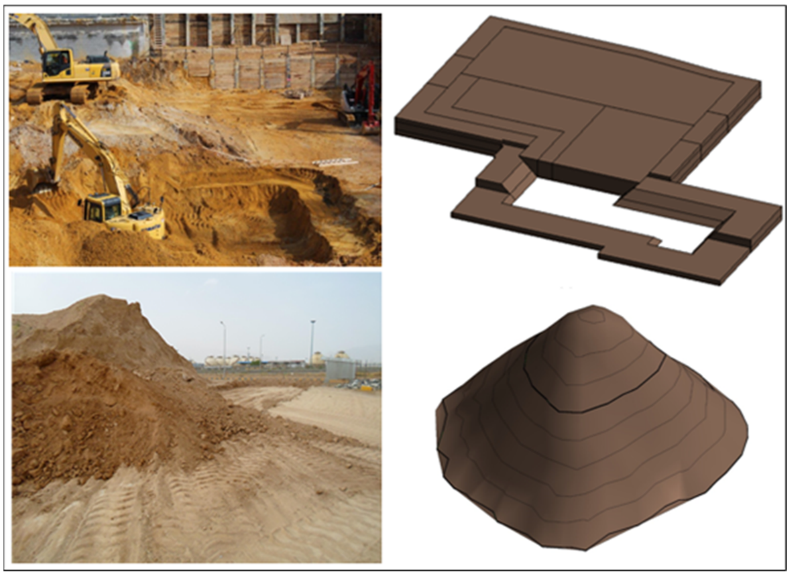

Figure 2. Physical and virtual entities of the construction excavation site and soil deposit/borrow.

4.2. Data Collection Tier

To capture the shape of the soil deposit/borrow and retrieve its volume, various enabling technologies such as volume sensors, laser range finders, light detection and ranging (LiDAR), 3D point cloud, topography and site surveying instruments and images can be deployed. These enabling technologies have their specific advantages and disadvantages regarding real-time data acquisition, accuracy, cost, manual/automatic process, etc. In this case study, due to cost limitations and taking advantage of the off-the-shelf tools that are common in construction sites, a Leica TS06 Total Station site surveying instrument was considered. Using this data acquisition tool, the current status of the excavated site and the shape of the soil deposit can be captured through numerous datapoints that are fed to the physical-to-virtual twinning tier in order to update the model to reflect the current status of the construction site. Figure 3 shows the output of this tier containing the required information to be transformed and fed to the next tier.


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Figure 3. Example of acquired data of the soil deposit and construction site.

In order to detect the locations of soil-carrying machinery, real-time locating systems (RTLS) can be used. Data collected from a real-time locating system can be integrated with Digital Twins [39]. Various studies in construction research and facility management [40,41] have been conducted for resource tracking, i.e., personnel, equipment and material. They have suggested related technologies, e.g., Ultra-wideband (UWB), Radio Frequency Identification (RFID), ZigBee, Bluetooth, Global Positioning Systems (GPS), for tracking resources. Since the CDT application for soil management deals with outdoor localization, GPS was found to be a suitable enabling technology to acquire real-time coordinates of the vehicles.

For the purpose of this study, the data acquired to capture the status of the soil deposit and construction site were sufficient for use in the next layers for the soil management purpose. However, in order to demonstrate other potential applications to extend the functionality of the soil management system as well as the integration of advanced technologies with the CDT framework, earthwork operations data were acquired for utilization in managing equipment and earthwork operations using simulation. Data collection for different activities can be performed using historical data, direct observation or sampling and expert judgment. Temporal data related to the trip to the dumping site and loading site can be acquired from timestamped GPS data. In this CDT application, direct observation or the sampling data collection method was used to acquire data regarding earthwork operation activities, i.e., loading the soil, trips to the dumping location, dumping the soil and trips back to the loading location. Table 3 shows the data for the soil loading activity. For the remainder of the activities, the data were obtained; however, for brevity, only the loading data are shown in Table 3.

Table 3. Acquired data of the earthwork operation activities (loading activity).

Truck No.	Duration (min)	Truck No.	Duration (min)	Truck No.	Duration (min)	Truck No.	Duration (min)	Truck No.	Duration (min)	Truck No.	Duration (min)
#1	15.35	#3	11.05	#2	10.55	#1	8.95	#3	11.25	#2	9.4
#2	13.05	#1	8.35	#3	9.3	#2	9.75	#1	12.4	#3	12.85
#3	12.7	#2	13.05	#1	11.3	#3	11.7	#2	10.6	#1	6.45
#1	12.65	#3	9.25	#2	9.1	#1	9.3	#3	11.4	#2	10.75
#2	12.25	#1	10.6	#3	9.75	#2	11.7	#1	9.45	#3	13.4
#3	12.05	#2	8	#1	10.75	#3	12	#2	10.75	#1	10.6
#1	11.75	#3	9.8	#2	11.5	#1	11.05	#3	10.25	#2	9.9
#2	11.55	#1	10.65	#3	10.3	#2	10.7	#1	13.3	#3	10.3
#3	11.4	#2	12.55	#1	11.6	#3	11.1	#2	9.95	#1	10.25
#1	11.05	#3	10.8	#2	11.7	#1	12.25	#3	9.25	#2	10.5
#2	10.6	#1	9.55	#3	11.45	#2	12.55	#1	11.75	#3	10.35
#3	10.6	#2	10.2	#1	9.7	#3	12.9	#2	9.6	#1	11.4
#1	10.55	#3	10.1	#2	12.3	#1	11.95	#3	10.65	#2	12.85
#2	10.45	#1	11.8	#3	9	#2	10.7	#1	10.2	#3	11.6
#3	10.3	#2	9.75	#1	13.5	#3	11.85	#2	11.2	#1	8.75
#1	9.75	#3	10.95	#2	7.5	#1	10.65	#3	13.5	#2	9.1
#2	9.4	#1	10.55	#3	14.8	#2	10.5	#1	11.45	#3	10.65
#3	9	#2	9.95	#1	10.8	#3	13.3	#2	10.7	#1	11
#1	8.65	#3	10.95	#2	8.85	#1	10.55	#3	9.7	#2	9.6
#2	7.9	#1	12.45	#3	12.2	#2	10.9	#1	10.8	#3	11.65

4.3. Communication Tier

The communication tier ensures the real-time synchronization of different parts of the CDT. Information technologies such as WLAN, 4G, 5G, HTTP and other communication and protocol technologies enable real-time data and information exchange among the physical, the virtual, analytics and prediction and services in the CDT. In addition to the IT infrastructure, a common data environment (CDE) or a data lake can be used to share digital models or store data that can be queried. The Internet was used for data exchange and a dedicated CDE was deployed for sharing models, storing acquired data and retrieving data in the current soil management application.

4.4. Physical-to-Virtual Twinning Tier

Due to data collection and transmission problems, missing and abnormal data might exist in the acquired data. To mitigate this problem, data pre-processing should be conducted for cleaning the acquired data [42]. Before integrating data with the virtual model, the collected data might need pre-processing to make the integration possible. Figure 4 demonstrates the extracted data to be fed into the Physical-to-Virtual Tier to update the virtual model.

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Figure 4. Pre-processing and data extraction from the acquired information.

Having the data cleaned, in the next steps these data can be integrated with the virtual model to update the model and mirror the latest status of the physical entity, i.e., the soil deposit/borrow status. The virtual model was created and updated using Autodesk Revit 2020 authoring software that was connected live to the CDE in order to constantly retrieve data and update the virtual model and share it with the relevant stakeholders. Figure 5 demonstrates the virtual model that later can be used for different purposes.

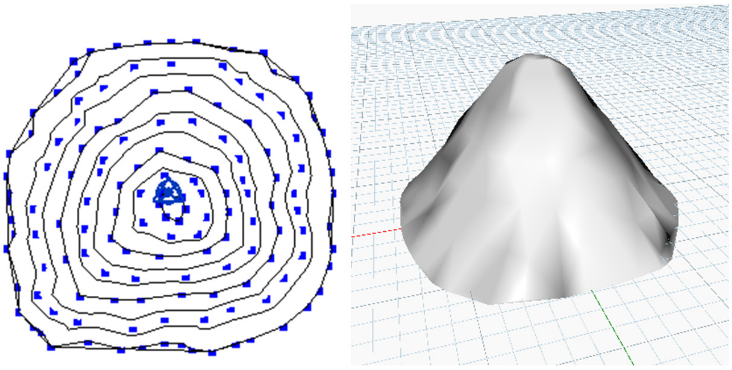

Figure 5. Updated model according to the acquired data.

Similarly, information from the construction site can be gathered and integrated with its virtual model to update the virtual twin of the construction site. Figure 6 shows the construction site virtual twin before and after acquiring data and updating the model.

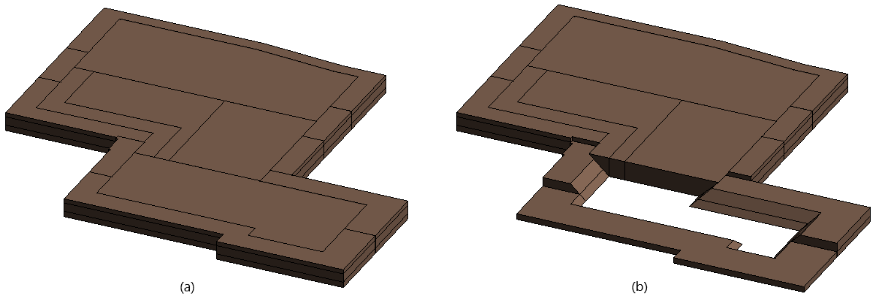

Figure 6. Construction site virtual twin (**a**) before updating, (**b**) after updating.

Since, in many cases, the soil deposit/borrow may be located outside the construction site due to several reasons (e.g., unavailable space, urban rules, project type, etc.), it is necessary to locate the virtual models at their actual coordinates. The integration between the current CDT and Geographic Information System (GIS) is advantageous in several ways for analysis and optimization studies, such as minimizing the travel time, finding optimal routes, managing machinery performance, cost minimization, etc. Finally, both the construction site and soil deposit/borrow models in a city context will provide a better understanding regarding their distance and relation visually (see Figure 7).

Figure 7. The locations of the hospital construction site and the soil deposit/borrow in a broader context (Autodesk InfraWorks).

4.5. Analytics and Prediction Tier

Earthwork operations are among the most important operations in construction sites. However, they are unpredictable in nature and include repetitive work, expensive equipment and large volumes of work performed in a highly uncertain environment [43]. Therefore, analyzing earthwork operations plays an important role in the project's productivity and its final cost and timeframe because different strategies have different impacts on the project's outcome. Discrete-event simulation is one way to improve the planning of earthwork operations [43]. In addition to the reason that simulation is a proper solution for soil management, the main idea of using simulation in this practical case is to demonstrate the CDT's capability to embed new technologies. Exploring details of simulation or discussion about other available solutions for soil management is out of the scope of this research.

In the current soil management application, a discrete event simulation was deployed to perform various scenarios regarding the earthwork operations to select the optimum amount of equipment (trucks, excavators/loaders) based on the project schedule. Next, based on the acquired data, a proper distribution (i.e., Normal, Poisson, Exponential, Beta distribution, etc.) that data fit into was identified using the histogram of the data. Following the identification of a distribution and its parameters, goodness of fit was performed using the Chi-Square test. Chi-Square statistic χ^2 can be obtained from Equation (1):

$$\chi^2 = \sum_{j=1}^{k} \frac{\left(N_j - np\right)^2}{np} \tag{1}$$

The n observations are arranged into a set of k class intervals or cells (C1, C2, . . . , Ck) where each class interval has equal expected probabilities of 1/k. In Equation (1), n is the total number of observations, Nj is the number of observations in cell j and p = 1/k. Based on comparing the obtained χ^2 to that from Chi-Square tables, the identified distribution can be accepted or rejected. The distribution is rejected if:

$$\chi^2_{computed} > \chi^2_{1-\alpha,(k-L-1)}$$

where α is the level of error accepted, $1-\alpha$ or p-value is the level of confidence, k is the number of classes, L is the number of estimated parameters and $k - L - 1$ is the degree of freedom. The earthwork operations consist of loading, trips to the dumping location, dumping and trips to the loading site. The data distributions for earthwork operation activities were detected using the process mentioned above. The identified distributions and their corresponding parameters for all activities are shown Table 4.

Table 4. Summary of activities' identified distributions and their respective parameters.

Activity	Identified Distribution	Distribution Parameter(s) (minute)
Loading	Normal distribution	μ = 10.84, σ = 1.45
Trip to dumping	Normal distribution	μ = 40.06, σ = 3.34
Dumping	Normal distribution	μ = 8.04, σ = 1.66
Trip to loading	Normal distribution	μ = 20.23, σ = 2.39

Developing the simulation model starts with the creation of system entities. In the current simulation model for the earthwork operations, trucks are the system's entities that arrive at the construction site on a specific time basis, e.g., constant time intervals or a distribution. Then, processes or activities such as loading, trips from the construction site to the dumping site, dumping and trips from the dumping site to the construction site are performed by the entities and resources, i.e., excavators/loaders and trucks. Additional components were also used to define and record various system attributes, e.g., trucks' arrival time, dumped soil volume, cycle time, flow time, etc. The simulation model needs to be fed by data. These data come from various sources, such as the collected data from sensors, GPS data, or data from models such as BIM and GIS models. In the simulation model, different components of the system have separate data input/output and data flow. The general concept and data flow of the simulation model for earthwork operations is shown in Figure 8. Extracted from the BIM model, a total volume of 181,940 m^3 of soil will be excavated. Assuming all of this volume needs to be transported, the simulation ends when 181,940 m^3 of soil is transported. Rockwell Automation Arena Version 14 was adopted to develop the simulation model of the earthwork operations.

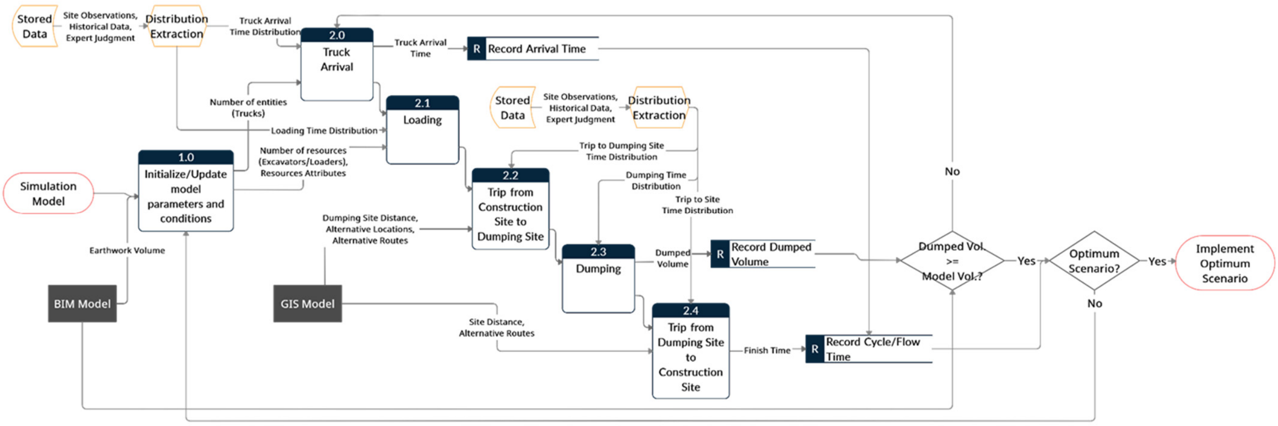

Figure 8. Data flow diagram for the earthwork operations simulation model.

In order to fulfill the desired confidence level, the number of simulation runs needs to be determined. The minimum number of simulations can be calculated from Equation (2):

$$R \geq \left(\frac{Z_{\alpha/2} S_0}{\varepsilon} \right)^2 \tag{2}$$

where S_0 is an initial estimation of σ calculated based on an initial number of runs of R_0 (e.g., ten runs), ε is an absolute error value, α is the risk level (therefore $1 - \alpha$ is the confidence level) and $Z_{\alpha/2}$ is calculated based on the Normal distribution according to the confidence level. An initial run with ten replications was performed to calculate S_0 according to each replication's cycle time (how long it takes a truck to complete one cycle) and a value of 0.41 was calculated for the standard deviation of the cycle times (S_0). Considering a 95% confidence level and a maximum error size of 0.1 as an average for the truck cycle time, the minimum acceptable number of simulation runs can be calculated:

$$R \geq \left(\frac{Z_{0.025} S_0}{\varepsilon} \right)^2 = \left(\frac{1.96 \times 0.41}{0.1} \right)^2 = 64.5$$

Therefore, a minimum number of 65 runs is required.

For the soil management case study, three scenarios were considered to perform the job in 8, 6 and 4 months. For each scenario, the proper amount of construction equipment needs to be determined considering the project's schedule. In the first scenario, 8 months (240 days) was considered in the project's schedule to complete the earthwork operations. Following the determination of the minimum required number of runs, 65 runs were performed with the initial model setup, i.e., two excavators/loaders and eight trucks and other attributes of the system (e.g., trucks' capacity, working hours, break time, downtime, etc.). After running the model, the initial strategy results were reviewed to evaluate the overall performance of the system and the adopted strategy. The simulation results of the first strategy showed that a total number of 325.9 working days would be needed to finish the operations; the daily production and the mean equipment utilization would be 558.27 m^3/d and 49%, respectively.

The output results indicated inefficiencies of the first strategy due to the following reasons:

- The project's schedule was not met;
- Daily production was not sufficient;
- The utilization of construction equipment was low.

Another operation strategy was established by adding four trucks to the existing eight trucks to improve the first strategy's inefficiencies. The results of the second simulation run with a total of 224.8 working days, daily production of 809.34 m^3/d and mean equipment utilization of 70% showed that the project's duration was met and the utilization of resources was satisfactory.

For the second scenario, 6 months (180 days) was considered for the earthwork operations in the project's schedule. Different strategies were implemented to evaluate the best strategies. For brevity, only the final results of the implemented strategies are reported in Figure 9.

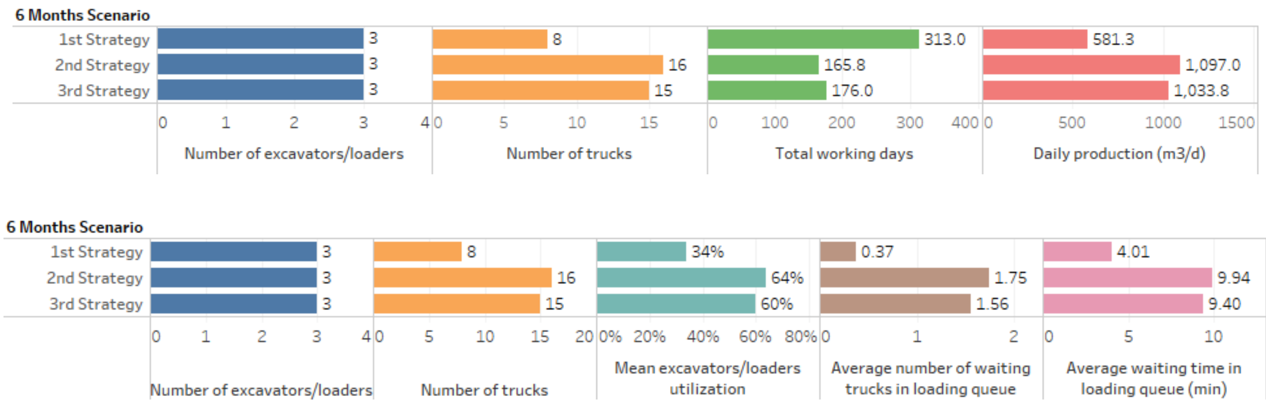

Figure 9. Simulation results of the various strategies for scenario #2.

Similarly, various strategies were simulated for the third scenario with 4 months' (120 days) duration to evaluate the best strategies. For brevity, only the final results of the implemented strategies are reported in Figure 10.

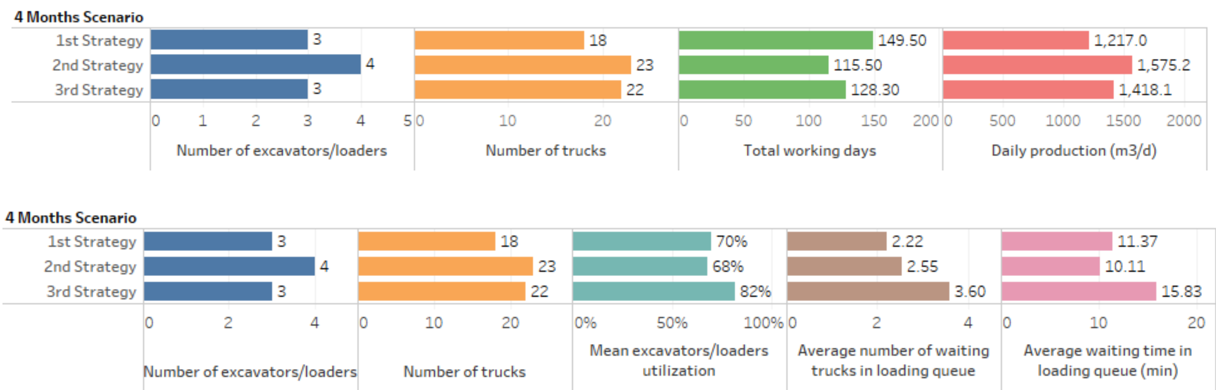

Figure 10. Simulation results of the various strategies for scenario #3.

The selection of the optimal strategy depends on various parameters such as the project's time and budget, the amount of available equipment, desired equipment productivity and waiting time.

4.6. Application Tier

Being fed by the lower tiers, i.e., the physical-to-virtual twinning tier and the data analytics and prediction tier, the application tier provides several benefits and services. In the current soil management application of the CDT, the updated virtual models of the construction site and soil deposit/borrow, the simulation results and the information outputs can be used to provide various services such as site progress monitoring, logistics and material supply, site management and resource allocation, claims management, etc. Following the model and data integration, the volume of existing soil in the soil deposit/borrow will be available to relevant stakeholders for information, decision making and managing upcoming activities. For this purpose, a "Soil Volume" instance parameter was created to present the soil deposit/borrow volume as the model is updated. In the case that the model is updated based on the data points output from the site surveying tools, a dynamo script was developed to calculate the volume and assign the value to the Soil Volume parameter in the authoring software. Figure 11 shows the results of the calculated volume of soil after the model update.

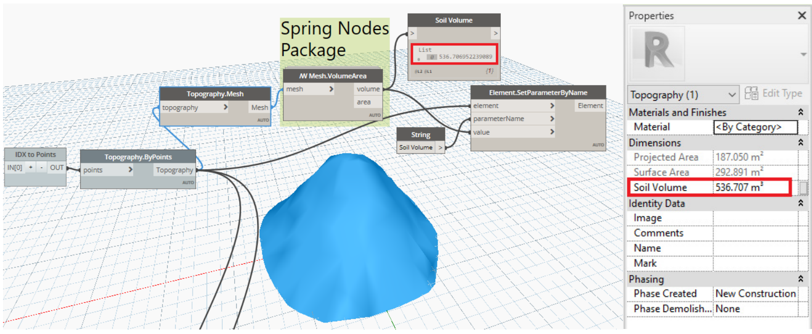

Figure 11. Calculating the soil volume and updating the model's parameter.

Informed decisions can be made based on these applications and, with the predefined configurations, criteria, or thresholds, controlling or actuating mechanisms can be enabled in the virtual-to-physical twinning tier.

4.7. Virtual-to-Physical Twinning Tier

Finally, proper decisions can be made or actuating mechanisms can be activated in the virtual-to-physical twinning tier. In this tier, the virtual entity/space acts on the physical entity/space and virtual-to-physical twinning happens. In the soil management application, it enables the construction managers to make decisions based on the real-time monitoring of the soil deposit/borrow status and construction site and meet the constant demands of the active subcontractors at the construction site for soil supply or soil deposit. In addition, a scenario with the proper amount of equipment was achieved to enable the monitoring of the earthwork operations' progress and the tracking of deviations from the project schedule.

In Section 5, the results and impacts of this study in the construction field are presented. In addition, further developments both in theoretical and practical perspectives for future studies are discussed.

5. Results and Discussion

After developing the Construction Digital Twin framework and implementing a case study based on the developed framework, various benefits and challenges were revealed. The beneficial aspects of the CDT can contribute to construction practice in several ways, as discussed below. The challenges of implementing and using a CDT, on the other hand, can provide the basis for future research and improvements.

5.1. CDT Impacts in the Construction Field

5.1.1. AI-Assisted Construction Management

Following the development of the CDT framework, the soil management case study was implemented as an application of the proposed CDT framework to demonstrate the benefits of using Digital Twins during the construction phase of projects. The simulation of the earthwork operations was performed as part of the CDT deployment in a real-world project. The simulation results in evaluating various "what-if" scenarios for optimum resource allocation and operations management proved the benefits of using CDT in assisting management bodies with their decision making. According to the authors' knowledge, it is common in construction projects to use traditional manual methods to manage soil that might not be particularly efficient or cost effective. The approach shown in this study offers the possibility of more control over the desired application through the analysis of valuable data. If integrated with high-performance instruments, such as industrial 3D scanners in the case of earthworks, it is possible to have a real-time report of quantities of materials and their position in the construction site, allowing for immediate and effective steering actions. If these data are integrated with other external information, such as traffic state, it is even possible to calibrate the handling process in order to mitigate or avoid impacts such as traffic congestion and its derived environmental damage. Machine learning and artificial intelligence can be adopted within decision support systems to make autonomous decisions or assist managers with their decisions and respond to dynamic site changes in a timely manner.

5.1.2. Filling Information Gaps in the Construction Phase

Since information gaps exist between the as-designed BIM models at the design phase and the as-built BIM models at specific delivery milestones or a project's hand-over, i.e., information gaps during the construction phase, the CDT can be implemented for the desired physical asset to fill information gaps. Although this continuous and uninterrupted flow of information from the design phase to the construction phase and then to the operation and maintenance phase is beneficial to owners or is required by them, general contractors can also benefit from the acquired enriched data through a CDT. These data can be used to monitor and track the construction processes or extract knowledge and insights to use in the ongoing project that the CDT is implemented for. Equally important, these data can be used in their future projects for a more accurate time and cost estimation at the time of tendering to propose better bid mark-ups or to develop more realistic project schedules for the construction phase. Traditional approaches use "construction norms" that are gathered from unstructured and probably unreliable sources of information to be used as a rough guideline to make future predictions or develop construction plans. Needless to say, this lack of adequate information will not render accurate plans or predictions. A key strength of the CDT compared to the traditional methods is the ability to have a rich structured database of the desired application with sufficient metadata to be employed in the construction phase. This is highly valuable, especially when it comes to future projects of the general contractor. At the same time, the continuous provisioning of data from the site allows for statistical analysis even in the same project, in particular when the project is highly complex and of a long duration, as with infrastructural projects generally. In those cases, the integration of collected data and a good dashboard reporting system can depict—at different levels of granularity—key data such as resource involvement, production, issues, bottlenecks in the supply chain, etc. Differently from usual productivity systems, the automation of data collection and processing reduces the risk of errors and the subjectivity of the collected data, while the AI algorithms can use the data to perform immediate predictive short-term and long-term scenarios.

5.1.3. Reusing the CDT and Enhancing Future Information Systems

Infrastructure projects such as roads, bridges, railways, tunnels, etc., might be typical in nature in many cases and only differ in some configurations and features such as location, size, capacity, etc. Once a CDT is developed to serve a specific purpose in a project, it can be reused in future projects with some adjustments. In addition, as mentioned before, the stored historical data of the construction processes are available to designers, domain experts and future CDTs to facilitate and optimize the development of future CDTs and construction processes. This will reduce the cost of CDT implementation and make it a long-term benefit for general contractors. The added value of the implemented CDT framework through the case study for the general contractor was the ability to replicate the implemented CDT in their other projects with some minor modifications due to projects' specific characteristics.

5.1.4. Data-Driven Construction Management

Since the construction phase is accompanied by numerous challenges and has a high degree of complexity, using the developed CDT framework in implementing several applications can assist general contractors in managing the construction processes more efficiently. Equipped with BIM and digital models, real-time data acquisition and communication technologies and data analytics and prediction, this data-driven CDT framework enables advanced construction management to better understand, predict and optimize the physical construction processes. The data-driven loop in the CDT and the physical and virtual twinning are proven effective for advanced construction management and improving construction efficiency, collaboration and reliability [18].

5.1.5. Real-Time Capturing of the Construction Status

As shown in the CDT case study for soil management, it was possible to catch and monitor the soil deposit/borrow status in real time or near real time, track the progress of the earthwork operations and update the models accordingly. The updated status of the construction site from the CDT along with the project's schedule or 4D models can be used to monitor and calculate schedule deviations. Using the current CDT enabled managers to have updated reports of the site status that could be extended for multiple other construction aspects instead of regular site visits to capture the status.

5.1.6. Improved Collaboration and Information Exchange

A CDT can facilitate collaboration and information exchange across domains. Taking a retaining wall in deep excavations as an example, when the wall nails are inserted and the temporary shotcrete facing is poured, the construction of permanent wall facing takes time to be finished. Therefore, a CDT for the retaining wall can monitor the temporary shotcrete facing, and any changes in the status of the temporary shotcrete facing can be reported to the designer for design modifications. In addition, safety warnings can be sent to safety management in the case of wall movements and collapsing likelihood. In another application of the CDT for high-volume concrete pouring (e.g., in slabs with large areas), information exchange and real-time status reports of the parts where concrete is poured and those parts where concrete pouring remains to be performed will facilitate the procurement and construction processes among the related parties for a more efficient project supply chain. These are the real applications to be implemented in subsequent research studies using the CDT framework. Compared to traditional static methods that do not necessarily provide time-to-time updated information accessible to relevant stakeholders, the implemented case study showed that the updated model and output data can be shared among the entities instantaneously.

5.1.7. Transparency and Data Reliability

The evolution of the physical is synchronized with the virtual in real time or near real time. In addition, data coming from the physical and information from the virtual are stored and can be accessed for future uses. The ability of a CDT to present a real-time status of the physical and retrieve historical data leads to a more transparent construction among stakeholders and it also makes the CDT a reliable source of information. Claims management can be considered among the possible benefits of this transparency and data reliability. Transparency contributes to claims prevention, and recorded data can be the basis for claim mitigation when a claim is raised. In a study conducted by the authors [44], it was revealed that in three earthwork contracts there was a significant cost overrun of 61, 21 and 86 percent increases in the initial contract sum due to several factors, contractual claims among them. In another contract, one of the main causes of cost overruns was the improper management of the existing soil at the construction site using traditional methods that consisted of manual site visits, irregular and offline information updates and lack of recorded data and, consequently, a situation where claims arose. The CDT in this case study provided updated information accessible to engaged parties with time-stamped data that facilitated management efforts and prevented invalid claims.

5.1.8. Improved Construction Logistics

A CDT provides information to the related actors and, by providing the current construction status and available materials, the delivery of equipment and materials for the current or upcoming processes can be facilitated. As mentioned in this study, examples of improved logistics are soil supply and concrete supply for various construction activities. In the soil management case study, the real-time status awareness of the existing soil enables the general contractor to manage soil supply for the upcoming activities in the project schedule that need soil for their tasks. Hence, possible project time extensions can be prevented as a result of improved construction logistics.

5.2. CDT Challenges

5.2.1. Data Collection

Due to the complexity of construction processes, using a suitable technology for data collection in implementing a CDT for a specific application/purpose is important. Achieving automated, real-time or desired-time intervals and cost- and time-effective solutions for data gathering would highly facilitate the implementation of a CDT in the construction phase.

5.2.2. Virtual CDT Components and Platforms Costs

A challenge that might arise due to the variety of tasks and activities in the construction process is that more than one authoring platform might be needed for digital modeling and developing the virtual twin. These extra costs can be mitigated in several ways, such as using free and open-source digital solutions. Another cost-effective solution that was implemented in this case study was using existing state-of-the-art and off-the-shelf technologies to develop the DT that were being developed independently of DT. In addition, reusing a previously developed CDT in future projects can reduce costs, providing economies for the general contractor.

5.2.3. Interoperability within Cyber-Physical Systems

As more than one virtual environment might be needed for CDT implementation, interoperability and automatic data and information exchange between different platforms, e.g., the modeling environment and simulation platform, might expose another challenge. The use of software solutions that support APIs, cloud computing, common formats and open standards, etc., are possible solutions to mitigate the interoperability challenges. Using common data types and software API in this case study facilitated the implementation of the CDT framework.

6. Conclusions

Industry 4.0 encompasses ample benefits for various industries such as manufacturing, aerospace, systems engineering, oil and gas, construction, etc. As one of the main concepts of Industry 4.0, Digital Twin bespeaks a new paradigm in the construction industry as a real-time virtual replica of a physical asset. Several industries, such as manufacturing, automotives, aviation and healthcare, are extensively using the concepts of Industry 4.0, but the construction industry is in its infancy in terms of adopting and implementing Industry 4.0 principles. Moreover, to date, most construction industry studies and practices have focused on implementing DT in the operation and maintenance phase of facilities and the use of DT in the construction phase has not been addressed sufficiently. This study was motivated to address the existing gaps by developing a comprehensive Construction Digital Twin framework and implementing the CDT framework in a case study while focusing on more than one monitoring technology as well as integrating the CDT with the socio-technical platforms and using simulation for the higher levels of CDT.

Building upon extant works on DT in various fields, a CDT framework was built relying on the existing literature in accordance with general contractors' processes, including several tiers and their respective enabling technologies for implementing Digital Twins during the construction phase of projects. Using the developed framework, a CDT case study was implemented tier by tier to validate the applicability of the framework. The results of the case study demonstrated the benefits of using a CDT in construction projects in terms of enabling construction management bodies to have a real-time status of the construction site and finding and implementing optimal strategies based on various "what-if" scenarios.

Each project type and construction process has its particular characteristics, specifications and requirements. Therefore, the DT architecture for each application or process might be different in terms of scale, components and elements needed for each tier. The CDT framework proposed in this study enables the general contractor to design their own DT architecture in a scalable and flexible way, depending on the specifications of each project or process. That means the components of each tier can be adjusted or combined depending on the typologies of works, budget, time, etc., to serve the purpose of the application that the CDT is designed for.

By implementing the CDT framework in the form of a case study, several benefits, such as AI-assisted construction management, filling information gaps in the construction phase, reusing the CDT and enhancing future information systems, data-driven construction management, real-time capturing of the construction status, improved collaboration and information exchange, transparency and data reliability and improved construction logistics, could be anticipated.

Inevitably, the implemented case study revealed some challenges such as data collection, CDT components and platforms costs, interoperability within the Cyber-Physical Systems and other limitations that need more investigation in future works. Using innovative enabling technologies for data gathering and high-speed transmission technologies for data transmission, deploying free, open-source and off-the-shelf digital solutions for decreasing CDT costs and using API-supported software solutions, cloud computing, common formats and open standards for interoperability issues could be a starting point for future developments.

This work brings novelty and contributes to the existing research on this topic by developing an enhanced CDT framework from the existing frameworks to fully respond to a general contractor's needs. It enhances industry practice by better information management in the construction stage of an asset or its related components, improving contractors' and owners' satisfaction. The uniqueness of the proposed research project lies in its integrated approach for applying the benefits of BIM and Industry 4.0 technologies in the construction industry as a comprehensive method applicable in real-world projects and supporting them at the construction phase. The proposed CDT approach is highly desirable since it enables actionable knowledge and effective decision making in the construction phase based on real-time data and performing "what-if" scenarios that, in turn, can reduce construction waste.

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