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Proposal of a conceptual model of digital twins for construction sites

Propuesta de un modelo conceptual de gemelos digitales para obras de construcción

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Abstract

Lack of proper information flow could drive the persistent challenges of low productivity and quality in the Construction industry. Digital Twin technology integrates physical and virtual environments, providing better data flow for more efficient management. However, current propositions of Digital Twins in Construction remain incipient. The literature indicates that they are poorly defined, with no consensus on their boundaries, components, or applications. Thus, unified conceptual structures are needed to highlight the role of Digital Twins in construction management, considering their potential to integrate various digital technologies. This study proposes a conceptual model for developing and implementing Digital Twins on construction sites. It focuses on managing and controlling physical resources, such as personnel, equipment, and materials. This model is part of a broader research project under the Design Science Research (DSR) methodology. It covers the stages of empirical studies on-site and a literature review to identify and integrate key conceptual, technical, and technological requirements for data acquisition, analysis, and transformation. The proposed model lays a foundation for decision-making regarding the infrastructure and integration of Digital Twins systems. It aims to combine multiple digital technologies to improve production monitoring and control, efficiency, collaboration, and quality in construction projects.

Keywords: Digital Twins; conceptual model; digital technologies; construction sites; physical resources.

Resumen

La falta de un adecuado flujo de información puede impulsar los persistentes desafíos de baja productividad y calidad en la industria de la construcción. La tecnología de Gemelos Digitales integra los entornos físico y virtual, proporcionando un mejor flujo de datos para una gestión más eficiente. Sin embargo, las propuestas actuales de Gemelos Digitales en construcción siguen siendo incipientes. La literatura indica que están pobremente definidos y carecen de consenso respecto a sus límites, componentes y aplicaciones. Por ello, se requieren estructuras conceptuales unificadas que destaquen el papel de los Gemelos Digitales en la gestión de la construcción, considerando su potencial para integrar diversas tecnologías digitales. Este estudio propone un modelo conceptual para el desarrollo e implementación de Gemelos Digitales en obras de construcción. Se enfoca en la gestión y el control de recursos físicos, tales como personal, equipos y materiales. Este modelo forma parte de un proyecto de investigación más amplio, desarrollado bajo la metodología Design Science Research (DSR). Abarca etapas de estudios empíricos en obra y una revisión de literatura orientada a identificar e integrar requisitos conceptuales, técnicos y tecnológicos clave para la adquisición, el análisis y la transformación de datos. El modelo propuesto establece una base para la toma de decisiones respecto a la infraestructura y la integración de sistemas de Gemelos Digitales. Su objetivo es combinar múltiples tecnologías digitales para mejorar el monitoreo y control de la producción, la eficiencia, la colaboración y la calidad en proyectos de construcción.

Keywords: Gemelos Digitales; modelo conceptual; tecnologías digitales; obras de construcción; recursos físicos.

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1. Introduction

The construction industry faces well-documented problems, including low productivity and quality, poor predictability, inefficient information flows and collaboration, waste, weak links with academia and research, and limited technological innovation (Farmer, 2016; Oesterreich, Teuteberg, 2016; Sawhney, Riley, Irizarry, 2020; Opoku et al., 2021). These problems stem from the unique, site-based, and dynamic nature of construction projects, which require constant information exchange among numerous stakeholders (Oesterreich, Teuteberg, 2016). Construction sites involve multiple simultaneous activities and rely on the dynamic interactions among personnel, equipment, and materials (Park, Kim, Cho, 2016; Turner et al., 2021).

Given these intrinsic aspects of construction projects and ongoing digital transformation, modern production management requires more accurate and reliable construction site monitoring (Hasan, Sacks, 2023). Monitoring and control guide projects by using metrics to compare actual and planned performance, drawing on feedback from production (Navon, 2007; Del Pico, 2023). The longer it takes to identify deviations between desired and actual performance, the greater the potential damage and the more complex and costly the corrective actions become (Del Pico, 2023). Traditional construction management often uses paper or verbal communication for key site information. Thus, manual production monitoring is typically laborious, slow, error-prone, subjective, and inefficient (Navon, Berkovich, 2006; Cheng, Teizer, 2013; Hasan, Sacks, 2023). Moving to automated, real-time data collection can improve efficiency and reduce errors (Cheng, Teizer, 2013; Akanmu, Anumba, 2020; Sacks et al., 2020). The concept of Construction 4.0 is gaining importance in this context. It signals a digital transformation in the construction industry by adapting Industry 4.0 trends and technologies (Sawhney, Riley, Irizarry, 2020).

An emerging concept from manufacturing, Digital Twins integrate the physical and digital worlds and have been explored as a promising solution for monitoring and efficiently managing construction production (Opoku et al., 2021). However, upon reviewing the literature, it is possible to identify a clear need for further research and advancements in Digital Twins within the construction industry, particularly regarding a common definition of their conceptual boundaries. In construction, the concept remains new, poorly defined, and lacks consensus on its use to solve practical industry problems. Sacks et al. (2020) highlight the lack of unified conceptual structures to better define the role of Digital Twins in construction management and in integrating existing digital technologies. Opoku et al. (2021) and Zhang et al. (2022) state that Digital Twins are advancing in the manufacturing and automotive fields, but remain relatively new in the construction field, with few practical applications.

In practice, current implementation barriers include the unclear definition of Digital Twin systems components and their relationships, the difficulty in defining and integrating enabling technologies, the lack of clarity regarding human-in-the-loop functions, and limited site-based design. These barriers lead to fragmented system development and hinder the scalability of Digital Twin solutions in real environments. This context led to the following research question: What are the minimum components, enabling technologies, and integration requirements necessary to operationalize Digital Twins systems on construction sites, thereby reducing the gap between theory and practice?

Given this research question, a literature review identified the ongoing conceptual, technical, and technological requirements for achieving a fully functional Digital Twin. Meanwhile, an empirical study investigated the case of the existing system Smart Twins 4.0, which represents a step forward in implementing a practical Digital Twin for construction activities, specifically in concrete wall construction. Based on the analysis, this study proposes a conceptual model of Digital Twins for construction sites to improve the management and control of physical resources (personnel, equipment, and materials). The model supports data acquisition, analysis, and transformation, establishing a foundation for decision-making on the systems infrastructure and integration of Digital Twins. It can combine capabilities and multiple digital technologies to deliver proper information and enhance production monitoring, while promoting efficiency, collaboration, and quality improvement throughout the construction process.

2. Background

The concept of Digital Twins was publicly and formally introduced in 2003 by Michael Grieves during his Product Lifecycle Management (PLM) Executive Course at the University of Michigan in the United States (Grieves, 2014; Tao, Zhang, Nee, 2019). Grieves (2014) attributes the creation of the term to John Vickers, a former collaborator at NASA. Initially, Digital Twin referred to a preliminary three-dimensional conceptual structure. However, since 2010, NASA studies have significantly influenced the evolution of the concept (Tao, Zhang, Nee, 2019).

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According to Grieves' (2014) perspective, a Digital Twin is a rich virtual equivalent to a physical product that contains three main dimensions: a) physical products in the real space, b) virtual products in the virtual space, and c) a two-way data and information connection between both. This comprehensive connection enables the Digital Twin to extend throughout the product's lifetime, providing manufacturers with information about its actual functioning and adding value for users (Grieves, 2014). Furthermore, Digital Twins enable the simulation of the product, its performance, and the entire manufacturing environment operation (Grieves, 2014).

The American Institute of Aeronautics and Astronautics (AIAA, 2020) provides additional characterization: Digital Twins are a set of virtual information constructs that mimic the structure, context, and behaviour of unique physical assets. The virtual model is dynamically updated with data from its physical counterpart throughout its lifecycle to inform decision-making. The key elements are: (a) a virtual representation (model), (b) a physical realization (asset or group of assets), and (c) the transfer of data or information (connection) between both. The value of a Digital Twin comes from shifting work from physical to digital environments, enabling valuable analysis and the prediction of future physical conditions.

The adoption of Digital Twins in the construction industry was relatively slow until 2019 (Opoku et al., 2021). Boje et al. (2020) proposed a conceptual framework, named Construction Digital Twin (CDT). It focuses on the progressive evolution of Digital Twin maturity based on BIM, but lacks clear implementation guidelines. Subsequently, Sacks et al. (2020) proposed Digital Twin Construction (DTC), a data-centric concept that combines Building Information Modeling (BIM), digital monitoring technologies, Lean Construction, and Artificial Intelligence (AI). This new approach for managing construction sites enables the collection of contextualized and accurate status information, supporting proactive analysis (Sacks et al., 2020). DTC workflows focus on both the building (product) and the construction-site activities (production). They cover the dynamics of physical resources and processes, representing a relevant socio-technical approach within data-centric workflows that involve the PDCA cycle. However, the authors do not specify the required operational components or clarify how the enabling digital technologies should be integrated. Thus, the literature lacks effective site-based frameworks dedicated to implementing Digital Twins systems.

In contrast with CTD and DTC, this study focuses on the general operational aspects of implementing Digital Twin systems, which aim to integrate physical and virtual environments through continuously updated bidirectional data flows, enabling data conceptualization, comparison between expected and actual conditions, and stakeholder collaboration to solve problems and generate value. These principles apply across both product and process dimensions, as well as at multiple scales. Another relevant point discussed is the temporal scale of data across the layers of Digital Twins. While some authors emphasize the importance of real-time communication, others, such as Abdelrahman et al. (2025), suggest that in domains like building and urban Digital Twins, depending on the application, real-time response may not be as critical as in other domains, such as manufacturing. Thus, the most critical aspect is to keep the response speed in sync with the decision-making window, given the defined plans.

Smart Twins 4.0, as described by Araújo et al. (2025), is an integrated system that uses the Internet of Things (IoT) and Building Information Modeling (BIM) to monitor and manage metallic formwork in concrete wall construction. The study included exploratory analysis, system development, pilot implementation on an actual construction site, and performance evaluation. By utilizing Radio Frequency Identification (RFID) technology, Smart Twins 4.0 tracks the location, condition, and maintenance of formwork on time through a mobile application connected to a Web-based BIM model. The system accurately reflected on-site construction progress and delivered timely, reliable data to support decisions on formwork use, maintenance, and quality control. It reduced errors, rework, and variability in wall quality while enhancing transparency and productivity on-site. Considering its operation and conceptual background, this study argues that Smart Twins 4.0 represents a step forward in implementing a practical Digital Twin for construction activities by enabling real-time connections between physical formworks, buildings, and their digital counterparts, including products and processes. Its current limitations include restricted data analysis capabilities, interoperability challenges, and limited generalization beyond formwork.

3. Research method

This investigation is part of a broader research project conducted under the Design Science Research (DSR) methodology, in which the conceptual model is the first artifact proposed. The approach is qualitative and pragmatic, specifically drawing on an empirical study, including the application and assessment of Smart Twins 4.0, as well as a literature review, as illustrated in Figure 1.

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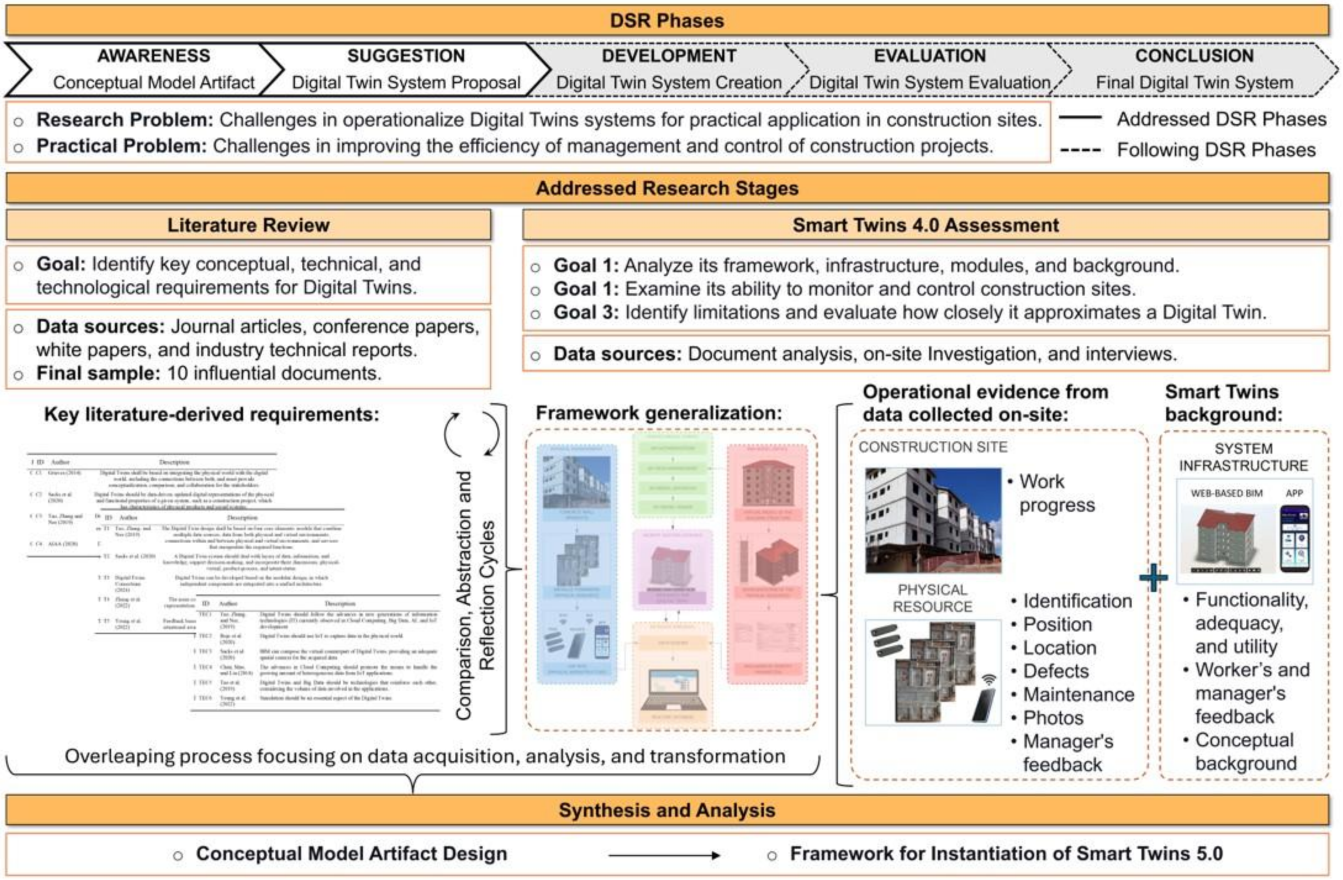

Figure 1. Research Method.

The first stage aims to assess the existing Smart Twins system and to determine how closely it approximates a Digital Twin. The activities included analyzing the system's infrastructure and modules, as well as reviewing functional capabilities for data acquisition, analysis, and transformation. The on-site data collection was conducted in a social housing project covering a total area of 21,856.63 m², with a built area of 19,618.78 m². It involves the construction of 20 buildings, each with five floors and four apartments per floor, totaling 400 housing units. The construction system employs sets of metallic formworks for the execution of cast-in-place concrete walls.

The construction site was selected from the projects of a partner company, which authorized tagging the metallic formwork. The choice was based on the construction system and the building typology (five-pavement buildings). The researchers collected data from July 8, 2021, to February 25, 2022, with the support of the site manager and team. A total of 28 construction site visits were conducted using Smart Twins for data collection and general assessment of the system. Two meetings with managers were held to validate findings, collect feedback, and discuss possible implementation strategies. Validation was based on analysis of results and photographic evidence. On-site data was gathered with the system's mobile app on an Android device equipped with a UHF RFID reader. The data included work progress and formwork ID, position, assembly sequence, defect and maintenance types, and evidence photos.

The literature review was exploratory, qualitative, and not systematic, and was conducted specifically to identify key conceptual, technical, and technological requirements for data acquisition, analysis, and transformation in Digital Twins, based on experience with previous stages of the broader research project. The initial set of relevant publications on Digital Twins in construction was identified through a Google Scholar keyword search for "Digital Twins Construction" (sorted by relevance) from 2020 to 2024. Only journal articles, conference papers, and white papers resulting from the first 50 documents related to construction phases and construction sites were included in the initial sample. Additional studies were retrieved through backward snowballing (investigating the reference lists of the selected papers) and forward snowballing (identifying more recent works that cited them), with the inclusion of relevant industry technical reports. This exploration process resulted in the identification of 10 final influential studies and the extraction of requirements. The identified literature-derived requirements were compared with previously

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defined Smart Twins requirements during a cyclical stage of abstraction and reflection and then correlated with the existing framework (Araújo et al., 2025), leading to a synthesis and analysis stage concerning how this framework could be generalized. This correlation aimed to align the proposed model with the practical challenges and constraints encountered in real construction environments. These findings supported the design of the proposed model.

4. Results and discussion

4.1 Smart twins assessment

During the empirical study, Smart Twins successfully registered defects and maintenance in the formworks, displayed statistical charts, and linked physical elements to their virtual BIM counterparts through automatic database integration. Through an inspection of 151 panels using Smart Twins, 100% exhibited external defects, and 98% exhibited internal defects. The most common defect identified was external wear (42%), followed by internal wear (28%), damaged mirror, the part in contact with the wall (19%), damaged ribs, which are the side components of the panel (7%), and perforated ribs (4%). Thirteen rounds of sequential readings were performed to verify the position of the formwork after assembly and before concreting, and no assembly errors were identified. The monitoring of metallic formwork and work progress, previously performed manually, was partially automated in the project, improving the formwork management process. Information was easily and automatically accessible through the Web-based BIM model, supporting strategic decision-making to reduce damage to formwork and, consequently, to the walls, which would otherwise require rework, increasing company costs and operational time. The system integrates Firebase as a non-relational database, BIM models via Autodesk Revit/Dynamo, and Android Studio for app development. GIMP handles the front-end, Vercel provides web hosting, and RFID UHF readers with passive tags capture data on Android devices. Despite the benefits, during the study, it was noted that the system requires improvements, including technical refinements, enhancements to data analysis, and regular updates to APIs and libraries. Furthermore, it was limited to a single physical resource and presented manual steps in data collection (semi-automated).

4.2 Digital twins requirements

The conceptual requirements identified established the main high-level ideas based on the key principles of Digital Twins to support the design of the conceptual model for Digital Twins in construction sites. These conceptual requirements are outlined in Table 1.

Table 1. Conceptual Requirements.

ID	Author	Description
C1	Grieves (2014)	Digital Twins shall be based on integrating the physical world with the digital world, including the connections between both, and must provide conceptualization, comparison, and collaboration for the stakeholders.
C2	Sacks et al. (2020)	Digital Twins should be data-driven, updated digital representations of the physical and functional properties of a given system, such as a construction project, which has characteristics of physical products and social systems.
C3	Tao, Zhang, and Nee (2019)	Digital Twins should form bidirectional and synchronized data flows, in which the interconnections of physical entities with their equivalent virtual components enable a stable closed loop for detection and control, keeping physical and virtual spaces synchronous and consistent.
C4	AIAA (2020)	Digital Twins should be dynamically updated with data from their physical twin throughout their lifecycle and inform decisions that realize the value.

According to these requirements, Digital Twins connect the physical world with the digital realm, enhancing human conceptualization, comparison, and stakeholder collaboration abilities. Data collection is crucial to ensure updates that reflect the dynamic nature of a given real-world system over time. The representation of physical and functional properties guarantees alignment with the fundamental principles of the real world, where status changes occur constantly. Moreover, representation, visualization, processing, and information generation are data-based, underscoring that Digital Twins are data-driven.

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It is important to highlight that, from the perspective of this study, the bidirectional and synchronized data flows in building construction are not necessarily automatic. After collecting raw data from the physical world and processing it in the digital realm, the loop may involve a human as a receptor in the physical world who receives the processed information and makes timely decisions, subsequently restarting the collection cycle. Thus, humans are fundamental in ensuring a stable and consistent closed loop. Although an actuator device may serve as a receptor in the physical world, enabling the loop to occur automatically in some cases, as seen in controlled manufacturing environments, this is not a standard rule in this study.

On the other hand, another important point from this study's perspective is that synchronization must be adjusted according to the speed necessary to make effective decisions based on each situation. For example, most work safety applications will require real-time feedback. However, for management and planning applications that do not demand immediate action, a longer response time window will be adequate to make decisions effectively and correct deviations without compromising the budget and schedule. Therefore, there is no reason to assume that the technological and computational costs of providing a real-time solution in these cases are prohibitive. Thus, the dynamics of responses are defined according to the situation addressed and the cost-benefit analysis. Ultimately, the goal of any Digital Twin is to solve real-world problems and deliver value throughout its lifecycle, considering the specific application.

Once the conceptual requirements have been established, the technical requirements outline the main internal components of a Digital Twin system, including the models, services, and connections involved, as shown in Table 2. A Digital Twin system for managing and controlling physical resources must be data-driven and capable of effectively handling data acquisition, storage, management, transformation, and analysis.

Table 2. Technical Requirements.

ID	Author	Description
T1	Tao, Zhang, and Nee (2019)	The Digital Twin design shall be based on four core elements: models that combine multiple data sources, data from both physical and virtual environments, connections within and between physical and virtual environments, and services that encapsulate the required functions.
T2	Sacks et al. (2020)	A Digital Twin system should deal with layers of data, information, and knowledge, support decision-making, and incorporate three dimensions: physical-virtual, product-process, and intent-status.
T3	Digital Twins Consortium (2024)	Digital Twins can be developed based on a modular design, in which independent components are integrated into a unified architecture.
T4	Zhang et al. (2022)	The main components of implementing a Digital Twin should include digital representation for construction sites, IoT, data storage, integration, analytics, and interaction with the physical environment.
T5	Yeung et al. (2022)	Feedback based on simulation in Digital Twins should generate data that provides situational awareness and knowledge about the building's behavior and its project.

According to the technical requirements, Digital Twins are composed of models, data, connections, and services. Each layer must be observed during the design process. The models may include geometric models, simulation models, etc. The services encapsulate the functions, shortening and facilitating the development path. However, ensuring interoperability between the different services is a challenge that must be considered when defining the connection mechanisms. Data is in all cores, layers, and dimensions, and it is essential for generating the information and knowledge that supports decision-making.

Besides the physical-virtual dimension, Digital Twins also deal with relationships between products/processes and their intent/status. In the construction industry, buildings are one of the final products, and they involve several processes during construction activities. On the other hand, the intent is contained in the plans and projects as a reference, while the status is updated over time. Both plans, projects, and status can be represented in Digital Twins. Their development can benefit from a modular design that integrates independent components, including independent tools for digital representation for construction sites, IoT, data storage, integration, analytics, and interaction with the physical

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environment, into a unified architecture. Simulation is also an essential component in providing situational awareness and knowledge for stakeholders, as well as supporting future analysis and predictions.

Once the technical requirements have been defined, the technological requirements in Table 3 guide the definition of specific tools, platforms, and innovations incorporated in this study. The leading technologies, defined as essential components of Digital Twins systems for construction, are IoT, Cloud Computing, Big Data, BIM, Digital Ecosystems, and Simulation.

Table 3. Technological Requirements.

ID	Author	Description
TEC1	Tao, Zhang, and Nee (2019)	Digital Twins should follow the advances in new generations of information technologies (IT) currently observed in Cloud Computing, Big Data, AI, and IoT development.
TEC2	Boje et al. (2020)	Digital Twins should use IoT to capture data in the physical world.
TEC3	Sacks et al. (2020)	BIM can compose the virtual counterpart of Digital Twins, providing an adequate spatial context for the acquired data.
TEC4	Chen, Mao, and Liu (2014)	The advances in Cloud Computing should promote the means to handle the growing amount of heterogeneous data from IoT applications.
TEC5	Tao et al. (2019)	Digital Twins and Big Data should be technologies that reinforce each other, considering the volume of data involved in the applications.
TEC6	Yeung et al. (2022)	Simulation should be an essential aspect of the Digital Twins.

According to the technological requirements, Digital Twins follow the general advances in new generations of Information Technology (IT). Unlike some authors, AI is not considered an isolated component in the development of a Digital Twin in this study. This understanding is despite recognizing that its use can optimize each defined technology individually or in an integrated manner, thereby improving the capabilities of the generated Digital Twin systems at various levels.

On the other hand, IoT plays an essential role in data collection. Incorporated into Digital Ecosystems, BIM can provide a robust set of geometry and semantics to form the spatial context for the updated data collected. Cloud Computing and Big Data are also critical in managing data across all cores, layers, and dimensions of the Digital Twin. While BIM is not commonly found in Digital Twins across other industries, it has gained significant importance in Digital Twins specifically developed for the construction industry. Besides its extensive representation capabilities, BIM already possesses several functions well-suited to the unique challenges of the construction context. BIM offers interoperability, scalability, and extensibility features, enabling its integration as a component of Digital Twins. Its consistent capacity for integration with IoT has been well-documented in the literature over the past few years.

Additionally, simulation modules are crucial components that warrant further exploration, particularly in Digital Twins that depict processes. Simulation can enhance situational awareness, analyze scenarios, and predict deviations. It is particularly valuable for increasing awareness of human behavior on construction sites, where activities significantly depend on human performance. Managing the workforce poses one of the major challenges in construction management and control. The advancement of digital technologies presents an opportunity to explore this potential within Digital Twins, providing insights and guidance for the future, despite current limitations in research and development.

4.3 Conceptual model of digital twins for construction sites

Integrating insights from Smart Twins with the conceptual, technical, and technological requirements for Digital Twins, as outlined in the literature, laid the foundation for building the artifact of this study. An abstraction and reflection process was conducted, besides a synthesis and analysis stage, resulting in a proposal for a conceptual model of Digital Twins for any construction site, illustrated in Figure 2.

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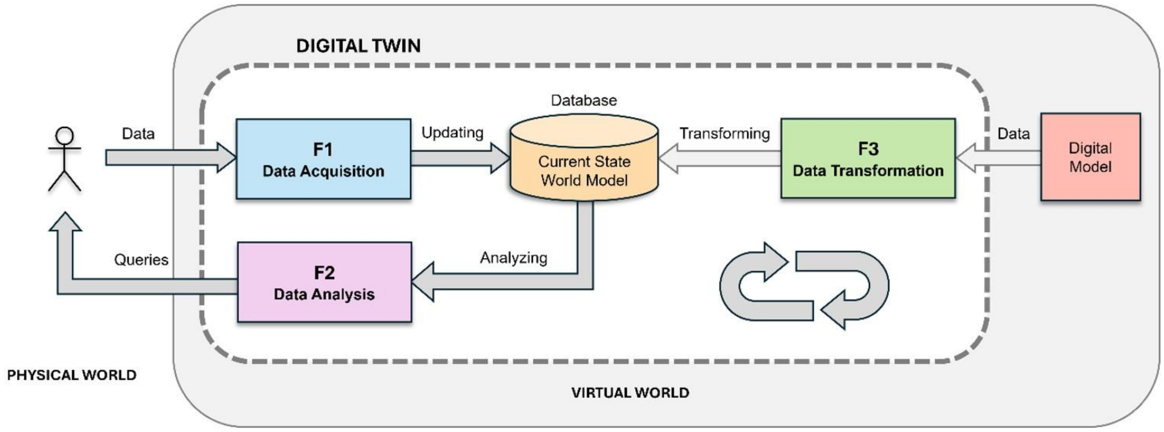

Figure 2. Conceptual model for Digital Twins.

The conceptual model was proposed considering (1) the goal of bridging the gaps between Digital Twins theory and practice at the operational level of construction sites by incorporating advanced digital technologies and simulation components to effectively enhance managers' decision-making during construction, promoting improvements in quality and productivity, and (2) the generalization of existing functions of Smart Twins. The idea of integrating established system modules with concepts from the literature was motivated by the need to expedite the technical and technological development of the Digital Twin in this study. It also ensured that a new version of the Smart Twins system could achieve the level of a Digital Twin before the development process began. The conceptual model represents a contribution to support the development of any Digital Twin for construction activities.

Figure 2 illustrates the interaction of Digital Twins with the real world, highlighting the cyclical flow of functionalities required for developing and implementing Digital Twins on construction sites. These functionalities embody the principles of modular design. They may include periodic table elements proposed by the Digital Twins Consortium (2024), although they are not limited to these elements. The external continuous line signifies the boundary between the virtual and physical worlds, while the dashed internal line delineates the limits of the Digital Twin in the virtual realm. The central box represents the Current State World Model, which comprises Cloud Computing databases and consolidates all the data and information required for a consistent equivalence between the virtual and the physical counterparts.

The three boxes highlighted in the figure, F1 - Data Acquisition, F2 - Data Analysis, and F3 - Data Transformation, are described as follows. The specific tools used among all those available to achieve the capabilities required in each box vary for each application.

• **F1 - Data Acquisition:** This box represents the functionalities required to collect updated and organized data from monitoring the physical world, encompassing all necessary data processing. This box features IoT capabilities and interacts directly with the Current State World Model, updating it according to work progress via the Cloud Computing database. Data sources can include multiple sensing technologies.

• **F3 - Data Transformation:** This box represents the functionalities needed to prepare and transform the BIM model into a Web-based BIM model. This box enables direct integration with the database through the capabilities of Digital Ecosystems, such as Autodesk Platform Services or NVIDIA Omniverse. The native data of the initial BIM model within the conceptual model remains static, as what changes over time is the status provided by the IoT, which is updated in the forged Web-based BIM. Thus, the BIM model is only loaded once unless there is a change in the original geometry or semantics. Furthermore, it remains unaffected by the other box since no information is returned directly to it.

• **F2 - Data Analysis:** This box represents the functionalities required to analyse and deliver processed data in response to queries from the physical world, supporting decision-making and actions there. Smart Twins had not explored box F2, which became one of the objectives of the future study. This box includes simulations and interfaces that provide the user with essential information necessary for establishing a closed

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bidirectional flow that will resume after decision-making. This decision can result in a corrective action or, if no deviation is observed, in the approval of the results. Multiple simulation methods and tools can be combined.

Figure 3 illustrates an example of capabilities and tools inside one of the boxes of functionalities from the conceptual model. The simulation is a component within the F2 box necessary for analysing and delivering data in response to queries for support in decision-making or actions in the physical world. Although the simulation is emphasized in the figure, the F2 box of functionalities also encompasses user interfaces and other data analysis tools. The data and information flowing through the model do not necessarily pass through all components within each box, as this depends on the application queries.

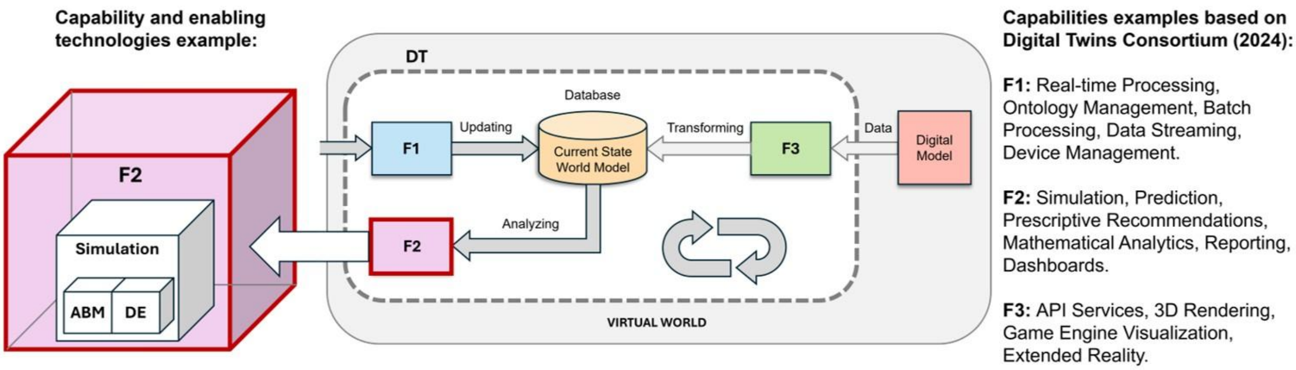

Figure 3. Example of components inside the box in the conceptual model for Digital Twins.

Figure 4 illustrates a framework for the instantiation of Smart Twins 5.0, an updated version of the existing system based on the proposed conceptual model. The existing data acquisition and ingestion capabilities are provided through IoT, specifically utilizing RFID tools, within the F1 box. In the F3 box, existing data representation and visualization capabilities are enabled by BIM and Autodesk's Digital Ecosystem Platform Services. The simulation proposed in the F2 box serves as a diagnostic tool that can be configured to be triggered either by the RFID system at each new building or upon user request. The F2 can supply the BIM model to F3, which serves as the geometric context for the simulations. Conversely, the F1 box provides real-world data that fuels the simulation.

Thus, the proposed model can be practically applied as a reference framework to guide the definition of technologies and tools, according to the intended Digital Twin application. It highlights the minimum components of a Digital Twin as sets of F1-F3 “functions” or applications; as well as it allows to a modular approach to enhance functionality by adding new Fs to the existing system: F1 represents the data flow from the environment and the physical asset to the virtual world; F2 represents the manipulation of the Digital Twin internal representation to provide information for decision-making, thus providing the data flow from the digital to the physical, considering the human-in-the-loop; F3 is a particular kind of F1 to deal with BIM models. Each F1-F3 would be composed of different capabilities to provide the transformation from input type to output type: F1 transforms each different data input into the internal representation of the Digital Twin, mainly anchored in BIM objects; F2s extract different types of data and provide diverse manipulation and processing to provide the functionality or output of the model. By using the boxes of capabilities as a starting point, practitioners can identify which components are necessary to support specific objectives, such as safety monitoring, quality control, or productivity management on the construction site.

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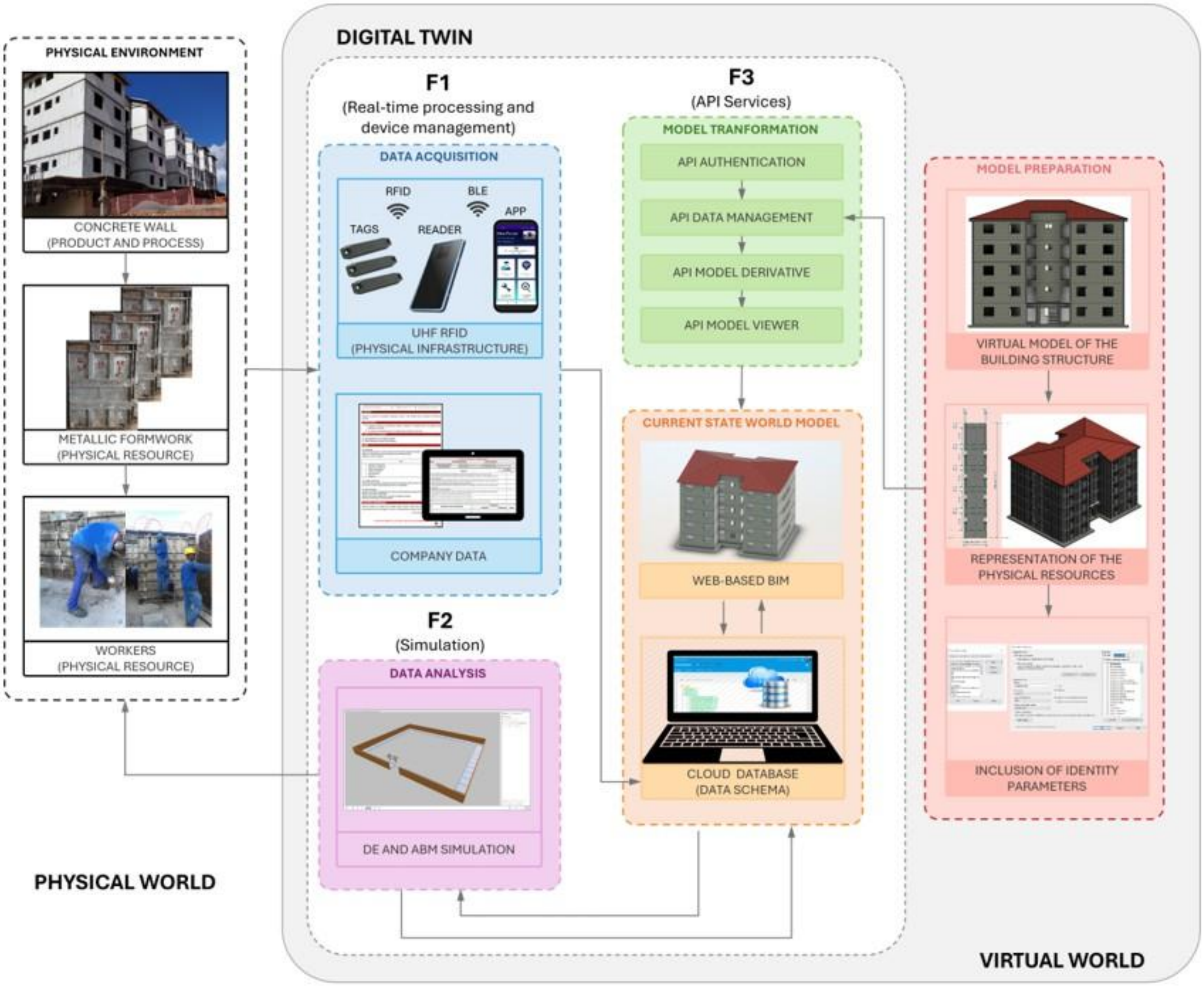

Figure 4. Framework for instantiation of Smart Twins 5.0 based on Araújo et al. (2025).

5. Conclusions

The primary theoretical contribution of this study is a closed-loop conceptual model of Digital Twins for construction sites. This model provides a foundation for decision-making on operational systems infrastructure and integration, aligning with the requirements of Digital Twins. The expected practical contribution is to improve production monitoring and control. Although designed for broad applicability, it has certain limitations and needs future testing in different contexts. Some specific technologies may require additional functional components, new boxes, or alternative connections between elements for proper alignment. For instance, integrating Blockchain for smart contracts could directly interact with the Current State World model. Its modularity allows future updates to boxes, but any changes require a deep understanding of the practical problem, the Digital Twin requirements, and additional abstraction and reflection. To enhance comprehension and generalization, the model intentionally simplifies real-world complexity. Thus, it does not explicitly address challenges in integrating heterogeneous systems across modules or potential interoperability issues in practice. Additionally, it does not explicitly represent human participation beyond decision-making in the physical world, which limits depiction of their broader role in Digital Twin environments (e.g., generating BIM models). Future research can further explore these topics.

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