# ENTERPRISE DIGITAL TWINS FOR STRATEGIC DATA UTILISATION FROM CONSTRUCTION SITES

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## Abstract

The progressive digitalisation of construction sites, driven by the deployment of digital technologies, presents organisations with the significant challenge of effectively extracting value from the surge in data production. This paper introduces the concept of '*Enterprise Digital Twin*' (EDT) as a new form of digital enterprise in the construction sector, which extends beyond the scope of individual construction sites and projects to enable a variety of data-driven operational and strategic insights for construction organisation. Despite its importance, there exists a notable scarcity of research in this area. This paper introduces the EDT concept, presents a review of the available literature, proposes an early conceptualisation, and discusses its challenges and opportunities. These are early contributions to this nascent area and lay the foundation for future research.

## Introduction

The construction industry is increasingly incorporating different digital tools and methods, such as Building Information Modelling (BIM), Wireless Sensor Networks (WSN), and Internet of Things (IoT) related technologies across the project lifecycle, including the construction phase (Statsenko et al., 2023). As a result, a large amount of operational data is produced in the construction industry and managed across geographically dispersed construction sites, supporting various functions such as procurement, quality assurance, supply chain, and logistics (Chen et al., 2024). Valuable insights can be untapped at both the project and enterprise levels through the exploitation and analysis of such extensive and diverse repositories of data, encompassing both structured and unstructured (You & Wu, 2019).

One of the pivotal technologies conceived for capturing and analysing data to deliver insights is Digital Twin. A Digital Twin (DT) is a digital replica of a physical entity, process, or system that enables a bidirectional information exchange between the digital and physical counterparts (Botín-Sanabria et al., 2022). Parvin (2021) stated that the information standard from enterprise to project is crucially important for digital twins to work in the construction industry. Research indicates a positive relationship between the degree of digitalisation of an enterprise through the use of DT and enterprise performance (Li & Liu, 2023). When augmented with other technologies, such as Internet of Things (IoT) and Artificial Intelligence (AI) , DT has the potential to provide real-time accurate status information and optimise ongoing design, plan, and production (Yitmen et al., 2023). Data integration is crucial because it allows businesses to utilise important operational data, which can yield new strategic and operational insights across diverse domains and functional areas. Yet, investigating how to effectively utilise this data from construction projects at the enterprise level is an emerging paradigm for both research and industry practice.

This paper explores the concept of EDTs within the construction sector. It highlights the necessity for EDT deployment and introduces a low-granularity conceptual architecture for EDTs. The methodology used to develop the EDT conceptual architecture is based on an extensive review of related concepts in literature and the guidelines established in existing reviews, such as this one. Furthermore, the paper examines the challenges associated with implementing EDTs, alongside the potential opportunities arising from their adoption.

## Literature Review

### Construction Digital Twin

Large contracting companies involved in major infrastructure projects usually manage construction projects with multiple geographically dispersed construction sites. Managing these construction sites at once within the same project can be challenging in terms of data generation, storing, processing, and visualisation (Hasan & Sacks, 2023). In the contemporary context, it is problematic that contractor organisations persist in relying on traditional methods to manage substantial volumes of data, owing to the absence of platforms capable of integrating data from diverse sources and types, making it very challenging to collect, manage, and exploit the generated data (Shamshiri et al., 2024). This is further challenged by the growing increase in size and complexity of data generated (Yan et al., 2020).

The collection of vast quantities of data also bears sustainability implications for the organisations involved. Storing large amounts of data in the cloud is not only expensive but also impacts the planet`s sustainability due to the emissions produced from data storage facilities (Vlăduțescu & Stănescu, 2023). The inadequate quality of visualisations and continued dependence on paper-based documents prevents managers and decision-makers from gaining clear insights and applying knowledge (Pan & Zhang, 2023).

Incorporating data into strategic management and decision-making processes can provide companies with numerous benefits (Ragazou et al. 2023). Although a large amount of data is available, many organisations fail to utilise it to their benefit (Ranjan & Foropon, 2021).

Digital Twin has emerged as a new technological concept that can address the management of smart construction site data for many reasons. DT has been adopted thus far only for a limited number of construction applications, and its concept has not been extended to the enterprise level. For instance, Sacks et al. (2020) proposed a comprehensive digital twin construction (DTC) system that integrates data from different activities to achieve closed-loop control systems. The DTC system extends beyond traditional activity-based monitoring and incorporates information from various sources. However, it is only activity-based and not operation-based. DT enables the integration of data, as highlighted by Salem and Dragomir (2022), indicating its role in integrating information technology and IoT for automating processes and managing activities related to building and urban structure operations. However, at the enterprise level, the exploration of this concept remains insufficiently addressed, with merely a handful of studies exploring its incorporation into Business Intelligence (BI) systems. For instance, Lopes and Boscarioli (2021) studied the implementation of BI and Analytics tools in the construction industry to improve management and decision-making. Rodrigues et al. (2022) studied the integration of BI with BIM in the construction industry, providing real-time data analysis for sustainable construction management and decision making. Thus, to address this important gap, in this paper we propose the introduction and early conceptualisation of the concept of 'Enterprise Digital Twin'.

## The Need for Enterprise Digital Twin

The importance of DT at the enterprise within the construction industry presents unique opportunities and poses critical challenges. While digital transformation presents the potential to attain excellence, it is crucial to establish connections between digital technologies, information, and strategic decision-making in order to tackle construction challenges (Balzano & Marzi, 2023). Previous research has put forward the importance of establishing a sustainable innovation ecosystem for industry and enterprise knowledge management and practices by interconnecting technological innovation, the business model, and the market (Yan, 2015; Yun et al., 2017; Yang & Yan, 2019). However, the success of this proposition heavily relies on the ability of collecting the necessary data to generate insights. An enterprise level digital twin is conceived as a socio-technical paradigm with the ability of capturing data from diverse resources. Mêda et al. (2021) focused on the concept of an incremental digital twin construction (DTC) system, which aims to integrate data from different activities to achieve closed-loop control systems. Merino et al. (2023) proposed a method for integrating data from construction activities, Building Automation Systems (BAS), and IoT using federated data models and ontologies. However, these studies concentrated solely on activity-based aspects, excluding considerations of operational foresight and business intelligence. This study will discuss the Enterprise Digital Twin concept and its role in leveraging data from different construction sites and organisation operations in the generation of operational foresight and business intelligence.

## Enterprise Digital Twin (EDT)

In the context of manufacturing, an Enterprise Digital Twin is defined as the utilisation of business-wide information to enable strategic decisions utilising asset and process digital twins across an organisation (Yan et al., 2022). Enterprise Digital Twins enable manufacturing managers to replicate all activities and interactions in the production chain, regardless of the number and location of assets, sites, suppliers, contractors, and sub-contractors involved (Kubelskiy, 2021). While some studies on EDT are available within the manufacturing sector, there exists a clear gap within the construction sector. This section introduces the concept of EDT in construction. EDT in construction is proposed as a virtual replica of an enterprise that incorporates people, processes, data, and technology to produce business outcomes. It is created by integrating technologies such as digital twins, cloud computing, analytics, artificial intelligence, and simulation.

An enterprise comprises multiple organisational units that collaborate to offer services that cannot be provided by a single organisational unit on its own. An Enterprise Architecture (EA) framework plays an essential role in defining principles and practices for creating and employing the information systems and technology infrastructure (Haki & Legner, 2021). EA frameworks form the foundation of the EA approach and serve the purpose of making the intricacies of the real world comprehensible and manageable for stakeholders (Scheer, 2023). Presently, various EA frameworks exist, including the Zachman framework, which was first introduced in 1987 as an early framework for EA (Zachman, 2003). Another prevalent EA framework is The Open Group Architecture Framework (TOGAF), which was initially developed as a methodology for the deployment of technical architectures but has since shifted its focus to EA over the years (Harrison, 2011). According to Riege and Aier (2009), Enterprise Architecture (EA) is widely recognised as an effective method for managing transformations and ensuring business/IT alignment. Therefore, an EA framework is employed in this research for initiating the early conceptualisation of EDT (Figure 1). This approach is guided by Zachman (2003) emphasis on addressing the what, how, when, who, where, and why aspects of information systems, mirroring the layers within the EDT conceptualisation that address the sourcing, integration, storage, analysis, and utilisation of data for decision-making in construction enterprises. Additionally, Harrison (2011) proposed that the Architecture Development Method (ADM) of The Open Group Architecture Framework (TOGAF) provides direction for developing architectures by following a series of stages, such as business architecture, information systems architectures, technology architecture, and others. A similar approach is mirrored in the conceptualisation of the Enterprise Digital Twin (EDT), where repetitive improvements are made at each layer to address the operational requirements of construction enterprises.

## Data Source

Nowadays, data generation has become a prominent aspect across all types of construction activities, resulting in an increase in the volume of data that needs to be integrated (Alaloul et al., 2021). The data layer, which harvests information from IoT sensors and various other sources including models, programs, among others, in addition to organizational processes like procurement, estimation, and logistics, gathers extensive volumes of real-time, near-real-time, and static data. Such data is available from various sources on construction sites, such as IoT sensors, drones, BIM data, and project management software (Merino et al., 2023) and can be used to generate important foresights about the effectiveness and efficiency of construction operations (Wang et al., 2023). This data can include real-time performance metrics of machinery, worker productivity, material usage, environmental conditions, and more. For an enterprise digital twin, collecting high-quality, granular data is crucial as it forms the foundation of both the operational and business intelligence insights.

## Data Integration

The significance of data integration is highlighted by Zhang et al., (2022) in the context of developing a digital twin that accurately mirrors the physical assets of construction sites. Within the context of EDT, the primary function of the data integration layer is to enable the seamless sharing and consolidation of data across various sources, ensuring that data and information is accessible, accurate, and consistent across the enterprise. Data integration layer has grown to encompass many different technologies and capabilities beyond Extract Transform Load (ETL) and ELT, which is just one-use case of data integration (Luengo et al., 2020), such as data virtualisation, data federation, cloud-based data integration services (e.g. Azure data factory, AWS Glue, etc.). These technologies are designed to gather, integrate, and transforms data from multiple sources into consistent, conformed, comprehensive, clean, and current information (Sherman, 2014). The data managed in the integration layer is critical to understand the status and performance of various enterprise components.

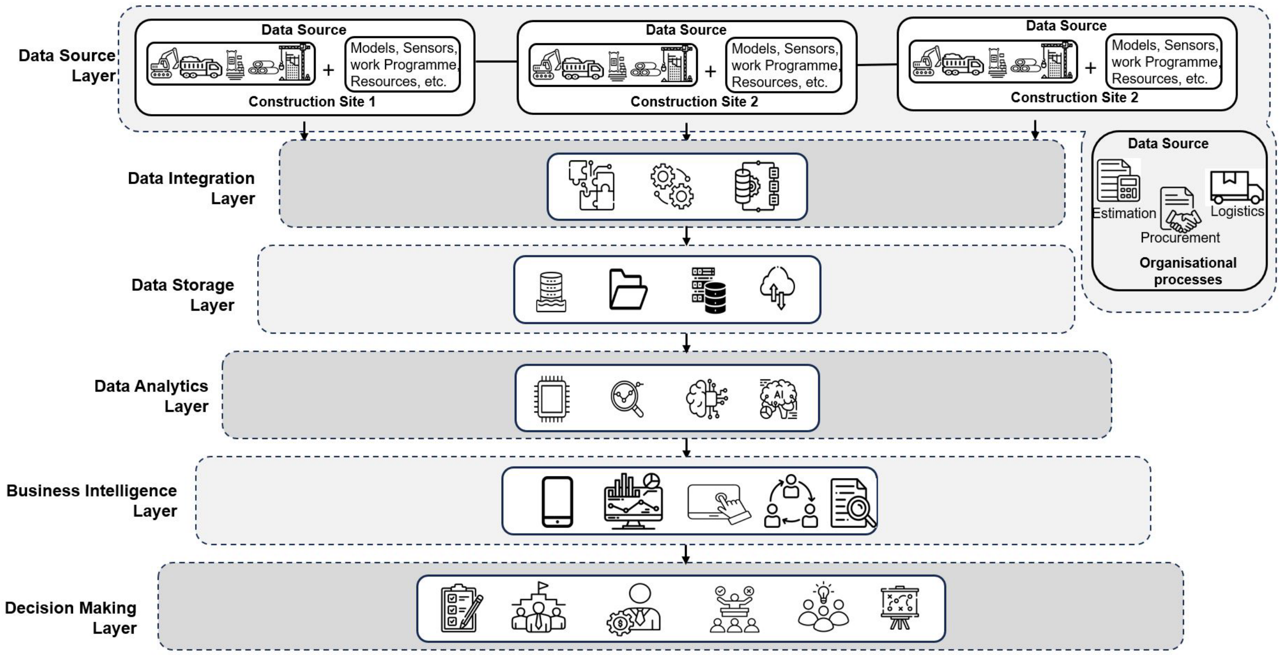


***Figure 1:*** Conceptualisation of Enterprise Digital Twin

## Data Storage

The data storage layer plays a crucial role in an enterprise architecture. It is responsible for persisting, managing, and utilising data within the organisation (Jones et al., 2022). Data warehousing is a data storage process that involves storing and preparing information separately from an organisation's routine transaction processing activities. It is designed to optimise the data for efficient access and analysis within the enterprise (Bharadiya, 2023). The layer in question serves as a repository for integrated data, including both structured data from data warehouses and unstructured or semi-structured data from data lakes. In this process, data from construction sites is transmitted to the data warehouse, where it undergoes data transformations such as cleansing, filtering, and aggregations that prepare the necessary to suit the enterprise required view of the data (Sherman, 2014).

Digital twin data, which are characterised by being sourced from multiple sources and having a large volume, necessitate the utilisation of big data storage technologies (Wang et al., 2023). The selection of a storage database for managing large amounts of data is contingent upon its ability to provide accessibility, scalability, high performance, and effective management. data storage solutions (e.g., cloud storage, database management system (DBMS), data warehouse and data lakes) are diverse, catering to different needs in terms of scale, performance, security, and accessibility. The selection of a data storage option is critical for supporting the varied applications and services an organisation relies on. Most studies have utilised cloud-based computing platforms for storing data which offer flexible and excellent backend access for computing applications (Betti et al., 2024). The scalability and flexibility provided by cloud computing enable the storage, processing, and accessibility of substantial amounts of data produced by the digital twin (Knebel et al., 2023). The selection of a data storage option is critical for supporting the varied applications and services an organisation relies on.

**Data Analytics**

The data analytics layer encompasses a suite of technologies, including Artificial Intelligence (AI) with Machine Learning (ML) as a subset, which are employed to conduct comprehensive analyses on accumulated data (Raschka et al., 2020). These technologies have become indispensable for organisations of all sizes and across all industries, as analytics and data-driven decision making have proven to be of paramount importance, enhanced decision-making is achieved through analytics and machine learning by offering practical insights derived from digital twin data (Arsiwala et al., 2023). Digital twin data can be utilised for multiple user services through advanced data analytics technologies. The utilisation of AI and ML technologies is important for the processing and analysis of data in the within the construction sector (Kazeem et al., 2023). AI and ML algorithms are indispensable for managing and analysing the substantial volumes of data produced by deep learning technologies (Kaur et al., 2020). These computational tools excel in discerning patterns and trends within datasets, thus enabling the extraction of pivotal insights (Bharadiya, 2023). DTs use AI/ML for predictive modelling, optimisation, and real-time monitoring, offering organisations valuable information for data-driven decisions and enhanced performance (Omrany et al., 2023). The analytics layer in an EDT utilises data analytics, AI, and ML algorithms to transform raw data into actionable intelligence to supports decision-making processes and identifies patterns and predictions. The processed data, which are supported by visualisation technologies (Wu et al., 2021), are ultimately accessible to end users in a straightforward and interactive manner through data visualisation.

**Business Intelligence**

The Business Intelligence (BI) layer aims to visualise information using tools such as dashboards and reports, transforming complex datasets into accessible formats that facilitate understanding and decision-making. Effective visualisation is a crucial component within the construction industry, as it plays a key role in facilitating communication and decision-making among team members (Lucchi, 2023). Lopes and Boscarioli (2021) highlights the role of BI in facilitating data-driven decisions, where stakeholders can quickly understand key performance indicators (KPI) and trends, enabling timely and informed decisions. One of the strongest aspects of digital twins is the ability to display sensor data in a virtual environment (Petri et al., 2023). Two commonly employed techniques for visualising digital twin data are colour coding in 2D and 3D schematics, performance dashboards, and time-series graphs, which are facilitated by visualisation platforms (Pal et al., 2023). Boje et al., (2020) posit that the implementation of data visualisation techniques in project management at smart and distributed sites alleviates the challenge of data inundation. According to Salem and Dragomir (2022), incorporating data from various devices and models can provide improved insights for enterprise decision-making through cross-checking and cross-referencing. For instance, visualisation tools in the EDT can be extended to enable an understanding of operations across all sites. This layer enables the evaluation of performance among different sites and the recognition of optimal strategies that can be implemented at the enterprise level.

**Decision Making**

The decision-making layer, on the other hand, is where strategic, tactical, and operational decisions are made based on the insights provided by the BI layer and other sources. Yue (2023) describes how the decision support ecosystem consumes analytical insights with business goals to guide decision-making. The decision support system (DSS) employs the results from business intelligence (BI) tools, such as dashboards and reports, to guide decisions that align with the company's strategic plan. This involves not only analysing past data but also utilising predictive analytics to forecast potential future scenarios. The system aims to provide a comprehensive view of the enterprise's operations and enable informed decision-making that supports the company's long-term goals (Yue, 2023). The abilities provided by these allow decision-makers to predict potential problems, assess alternative solutions, and take measures. Yan et al. (2022) highlight its impact on strategic planning, where predictive insights can shape the direction of construction projects and broader enterprise initiatives. They argue that predictive insights derived from the digital twin's analytics can significantly influence the planning and execution of construction projects. For instance, by predicting the impact of various factors on project timelines and costs, enterprises can make informed decisions that optimise resource allocation, mitigate risks, and enhance overall project outcomes (Yan et al., 2022). Sacks et al. (2020) state that the insights derived from the lifecycle of the digital twin significantly contribute to operational excellence and competitive advantage. Therefore, the digital twin at the enterprise level can become an indispensable tool for continuous improvement and strategic decision-making using data from across smart construction sites and business functions.

## EDT: Challenges and Opportunities

The implementation of EDTs in construction projects involves different technical challenges that need to be addressed to fully leverage their capabilities. Construction projects often generate large amounts of data in different formats due to the application of various systems and technologies (Himeur et al., 2023).

Advanced data management and interoperability solutions are necessary to integrate this data into an interconnected digital twin. The challenge is made more difficult due to the requirement for timely updates of data to keep the digital twin accurate and relevant (Borrmann et al., 2015). The potential to address this challenge lies in the adoption of recognised and accepted formats (such as XML, CSV, IFC, JSON, etc.) and protocols for storing and exchanging data that ensure compatibility and ease of use across different systems and applications employed by organisations in construction projects. However, as organisations pursuing EDTs are likely to be face complexity and scale challenges, standardisation, and integration across the various areas of the business become key (Faith and Tori, 2020). Semantic Web concepts such as the Enterprise Knowledge Graphs (EKG), a formal model to represent and manage enterprise information at a semantic level, can play a key role in integration.

Privacy issues emerge when encountering confidential data regarding project sites, designs, and staff members (Zhang et al., 2022). The nature of the data gathered and utilised by EDTs may encompass sensitive information, giving rise to issues regarding individuals with authorised entry to such data and the way it is used. Defining the roles and responsibilities for data management and ensuring compliance with relevant regulations can assist in mitigating privacy concerns by instituting well-defined policies for data access, usage, and sharing (Coupaye et al., 2023).

Security is an additional issue in relation to EDTs, as these digital systems are susceptible to cyber threats, like any other digital system (Faleiro et al., 2022). Potential interconnectedness between digital twins can present a major security risk, as a breach in one system has the potential to compromise the entire network, making it susceptible to cyberattacks (Faleiro et al., 2022). Protecting EDTs from such threats requires the implementation of advanced cybersecurity measures, including encryption, secure data storage and transmission protocols, and regular security audits (Lu et al., 2017). This includes the use of firewalls, intrusion detection systems, and regular vulnerability assessments by organisations.

Overcoming technical challenges and addressing organisational challenges are both necessary to leverage EDTs in the construction industry. The workforce must possess a high level of digital literacy and technical skills owing to the intricate nature of DTs (Hou et al., 2020). This encompasses proficiency in data analysis, an understanding of digital twin software and platforms, and the ability to comprehend and act upon the insights provided by DT at the enterprise level (Himeur et al., 2023). To address this challenge, it is necessary to implement training programs and recruit individuals with the necessary digital skills. Moreover, fostering a culture that promotes continuous learning and adaptation to stay abreast of technological advancements is important (Howard et al., 2017).

EDTs require organisations to develop and implement customised training programs to enhance the digital proficiency of their existing workforce and acquire new talents to address potential gaps in competencies (Agrawal et al., 2023). Continuous training is essential to maintain relevance in the face of fast-paced technological advancements. Implementing EDTs in construction initiatives frequently requires changing normal procedures and operational patterns (Riss et al., 2020). One approach to improving project management is to incorporate real-time data analysis and decision-making, as well as utilising the digital twin's predictive capabilities to refine procurement, scheduling, and risk management processes (Ragazou et al., 2023). Finally, due to the likely need for process reengineering that have the potential to cause disruptions and face opposition, the transformation require effective leadership and transparent communication regarding the advantages to all parties involved (Müller et al., 2024).

The implementation of EDTs in the construction industry presents many opportunities for innovation, construction practices, and the development of new business models (Kulkarni et al., 2019). New business models can be developed by leveraging the insights and efficiencies obtained from EDTs. Construction firms can enhance their value proposition by providing data-driven services that diversify revenue streams and foster long-term client relationships by offering value beyond project completion. For example, EDTs facilitate the construction of sustainable buildings by improving planning and resource allocation. The optimisation of energy use, selection of sustainable materials, and integration of renewable energy sources into new projects can be facilitated by EDT, thereby aligning with global sustainability goals (Riss et al., 2020).

To take advantage of these opportunities, construction companies need to cultivate an environment that encourages innovation, collaboration, and standardisation, that are key enablers to transformative projects (Hook et al., 2022) such as EDTs. They also require exploring partnerships within their supply chains to enhance the connectedness that is key to EDT as well as allocating the resources to acquire essential technologies and develop and acquire the necessary competencies.

## Conclusions

The concept of Enterprise Digital Twins (EDTs) in the construction industry is emergent, driven by the exponential increase in data availability due to the widespread adoption of digital technologies on construction sites and beyond. Recognising the emergent nature of EDT within the construction industry, this paper attempted to provide a balanced perspective about EDTs. The paper presented a low-granularity architecture model with six layers for EDTs for construction organisations. It highlighted the importance of EDT in the transition towards a more interconnected and data-driven method for managing and executing construction projects and organisations. It also outlined some key challenges such as interoperability, privacy, and security, as well as some of the organisational challenges.

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