Towards Resilient Construction Logistics with Digital Twins

Fatemeh Massah
Pervasive Systems
University of Twente
Enschede, The Netherlands
f.massah@utwente.nl

Abstract. Efficient logistics management is key for maintaining project timelines, controlling budgets, and enhancing productivity and promoting sustainability in the construction industry. However, challenges such as delays in material delivery, equipment breakdowns, and labor shortages require effective managed to prevent significant disruptions. This research explores the application of digital twin (DT) technology to optimize construction planning and execution through real-time monitoring, simulation, and analysis. By leveraging advanced sensing and communication technologies, this study aims to develop and validate DT models tailored for construction logistics. The anticipated outcomes include improved decision-making, enhanced collaboration, and increased efficiency, which are expected to result in reduced costs and shortened timelines. The findings have the potential to significantly boost the competitiveness and operational efficiency of the construction industry.

Keywords: Digital Twin · Construction Logistics · Resilience · Data-Driven Insights.

1 Introduction

The construction sector needs to continue advancing technology adoption to address specific challenges and maintain its competitive edge. Despite the substantial long-term benefits, the industry has been slow to embrace new digital technologies due to, e.g., the required upfront investments [1]. A prominent technological trends is digitization, which impacts individuals, communities, and nations [16]. However, technical challenges specific to the construction sector hinder the pace of digitization. Deploying solutions across geographically dispersed construction sites presents one of the major obstacles [10]. Technologies such as Building Information Modeling (BIM) hold promise [29], yet their global adoption remains sluggish. This reluctance is driven by perceived risks and the complexities involved in the development and implementation of these technologies within the industry [1, 11].

In recent decades, the built environment has become more efficient and sustainable. New project management methods, enhanced by IT advancements, address real estate owners' demands for timely, high-quality projects that meet strict environmental regulations [7]. While industries such as automotive, manufacturing, and services have leveraged IT to enhance their competitiveness, the construction industry has struggled to keep pace, lagging behind various other sectors [2].However, the construction industry has also seen notable advancements, such as the increased adoption of Building Information Modeling (BIM) and DT technologies, which enhance project visualization, coordination, and management [18]. These technologies are driving improvements in project efficiency and sustainability, demonstrating the industry's capacity for innovation. Despite advancements, the construction industry struggles with low productivity, poor reputation, unpredictability, fragmentation, and insufficient R&D investment [27]. Overcoming these challenges demands ongoing integration of advanced technologies and improved practices to maximize digital transformation benefits.

Since its inception in the early 21st century, DT technology has rapidly gained traction and is poised to become a widely accepted and implemented innovation [14]. DTs generate virtual replicas of physical objects or processes, enabling the simulation of real-world behavior, analysis of effectiveness, and performance enhancement for improved business outcomes [19]. The maturation of key technologies such as low-cost storage, powerful processing capabilities, and reliable high-speed networks has facilitated this advancement [4].

To achieve widespread acceptance in the construction industry, DT technology must effectively address its primary challenges [27]. This innovation promises numerous benefits for the construction sector, including improved project planning, enhanced operational efficiency, better risk management, and cost savings [3, 30, 12, 6]. As a result, both industry and academia are increasingly focused on integrating DT concepts, with major companies adopting them in their products and researchers exploring their technological and business implications.

This paper is structured as follows. Section 2 provides a problem statement and a review of prior research in this domain. Section 3 outlines the anticipated project's methodology, discussing the research design and expected results. Finally, Section 4 concludes the paper by summarizing the findings and proposing future research directions.

2 Problem Statement and Related Work

2.1 Problem Statement

Construction logistics processes are frequently disrupted by various factors, including severe weather conditions, raw material shortages, extended waiting times, and system failures. These disruptions pose challenges for managers and decision-makers in identifying optimal strategies for logistics management, as they lack comprehensive analytical insights. Despite being one of the largest industries, the construction sector has been insufficient in adopting advanced

methodologies for effective data and model utilization. Many related industries could achieve higher efficiency if the construction industry adopted more advanced optimization techniques. As the construction sector is a critical part of the supply chain, inefficiencies and disruptions in its processes can have a ripple effect, impacting the performance and productivity of other industries. One of the main obstacles to achieving these insights and improvements is the absence of a comprehensive data management system. One potential obstacle to obtaining these insights might be the absence of a comprehensive data management system. Construction logistics generate a plethora of data types that must be collected, referenced, and synchronized to be effectively utilized by decision-makers. The work envisioned in this paper aims to demonstrate how DTs can significantly enhance the construction industry by providing real-time insights. DTs can be either data-driven, model-driven, or a combination of both. This research will explore various types of DTs and their applications, focusing on how they can improve decision-making processes, optimize logistics, and enhance overall efficiency in construction projects.
Research Question: How can the implementation of DT technology in construction logistics enhance real-time, data-driven decision-making and improve overall efficiency in the construction industry?

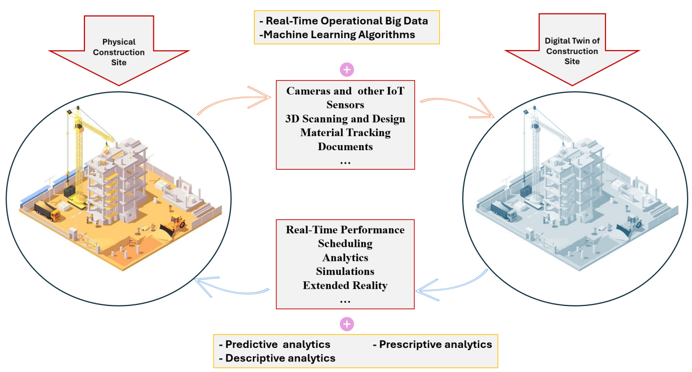

Fig. 1. Proposed informal conceptual framework for the digital twin in an construction site

The research aims to investigate the utilization of data, especially from DT models, across various domains within the construction industry. By exploring how this data can enhance construction logistics networks, the study addresses gaps in the adoption and integration of data-driven approaches. A particular focus is on how DTs can increase or maintain operational efficiency while enhancing sustainability and resilience in construction processes. Fig.1 in this paper illustrates the proposed informal conceptual framework for the DT in a construction site. Ultimately, this research seeks to improve operational effectiveness and address critical environmental and resilience challenges in the industry.

2.2 Related Work

Construction Industry Logistics And Disruptions. The construction sector faces challenges like fragmentation, waste, low productivity, cost overruns, and disputes [26, 15]. underscores the need for integrated systems to improve outcomes [9, 31]. [32] highlight how fragmented project teams and unpredictable conditions heighten supply chain vulnerabilities in construction. Implementing solutions such as Building Information Modeling (BIM), supply chain integration, and improved logistics can enhance efficiency and resilience.

Data-Driven Insights For Construction Logistics. The significance of integrating information in logistics networks is widely recognized across different sectors. Researchers identify it as a key element in achieving efficient logistics, including lean construction and successful project execution [17]. [8] emphasized that effective data exchange and communication are important prerequisites for enhancing performance in the construction industry. It is important to recognize and assess the historical context and integrated perspectives of communication processes to better understand their development and impact. The construction industry is inundated with vast amounts of data, and emerging IT technologies show great potential for effectively processing this information. However, comprehensive reviews on technological and organizational changes in the Big Data context, especially throughout the entire project life cycle, are lacking [25].
In summary, existing literature highlights data integration in construction logistics but overlooks Big Data's impact throughout project life cycles. Our research addresses this by analyzing the effective use of these technologies to improve outcomes and efficiency.

Digital Twin In Construction Industry. Construction remains one of the least-digitized industries [20]. To prevent escalating building costs, industry leaders are increasingly relying on digital transformation as a key strategy [13]. As the architecture, engineering, and construction sector embraces the digital age, technologies for sensor data monitoring, secure data management, and engineering system optimization are becoming more influential in the design, construction, and operation of built assets [5]. However, despite these advancements, there remains a significant gap in effectively integrating Big Data technologies across the entire project lifecycle, which hampers the full potential of digital transformation [28, 24].

While some research explores data-driven insights in logistics, there's a gap in how to gather real-time data for decision-making. Few studies address DTs in construction, particularly their role in logistics efficiency. Recent reviews highlight DTs' potential but point out challenges like data integration and scalability [22, 21]. Our research aims to fill these gaps by focusing on practical DT implementations in construction supply chains to enhance real-time decision-making.

3 Methodology

This research investigates the impact of data-driven insights and DTs on the efficiency of logistics networks in the construction sector, using diverse research methodologies to provide a comprehensive analysis.

3.1 Research design

To achieve the study's goals, the research will describe the functionality and objectives of a DT for construction, gather data from real-world case studies, develop a preliminary DT design, and refine it to ensure accuracy and reliability. For the design and development of the necessary artifacts, we followed the Design Science Research Methodology (DSRM) proposed by [23]. We chose DSRM for its systematic approach, integration of theory and practice, and support for iterative refinement. These artifacts are essential as they address the specific problems and objectives of our study. Fig. 2 provides an overview of the research methodology anticipated in this study.

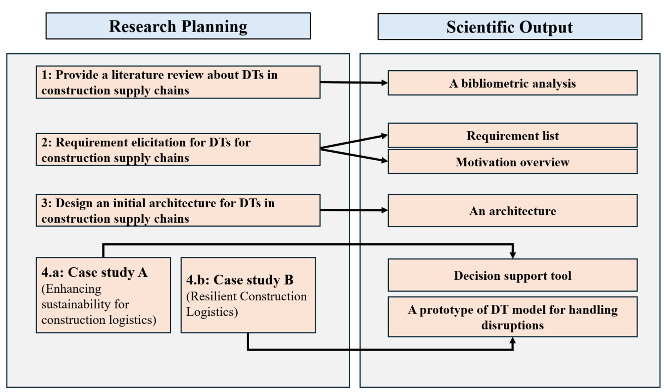

Fig. 2. An overview of the research methodology

The DT design will use synchronized data to create a virtual representation of the logistical network, offering real-time insights and predictive analytics. This model will simulate scenarios to anticipate disruptions and optimize resource allocation by employing advanced data processing and predictive algorithms.

This study aims to demonstrate the potential of DT technology in enhancing construction logistics management by addressing key objectives and overcoming potential obstacles.

3.2 Expected Results

The construction industry heavily relies on efficient logistics for timely project execution, while decision makers increasingly seek real-time, data-driven insights to optimize performance. This dual need highlights the urgency for more effective logistics management strategies. Recent advancements in digital technologies like IoT, cloud computing, and predictive analytics are transforming logistics operations in construction. These technologies enhance visibility, efficiency, and responsiveness across supply chains by enabling real-time monitoring and management of logistics processes.
DT technology could potentially enhance the resiliency and sustainability of construction logistics by enabling the simulation of various disruption scenarios and developing robust contingency plans, ensuring quick recovery from unexpected events. This proactive approach minimizes downtime and maintains project continuity. Additionally, DTs optimize resource usage and reduce waste through precise demand forecasting and efficient supply chain management, contributing to lower carbon emissions and a more sustainable construction process overall.

In this research, DTs will provide real-time insights for proactive decision-making in construction logistics. By monitoring inventory, equipment, and transportation, DTs will help anticipate bottlenecks, optimize resource allocation, enhance efficiency, and cost-effectiveness. Additionally, DTs will improve resiliency by enabling quick recovery from disruptions and support sustainability through optimized resource usage and reduced waste.

4 Conclusion and Future Research

In recent years, the integration of advanced technologies in construction logistics management has become increasingly prevalent, enabling decision-makers to leverage data-driven insights for more efficient and risk-averse processes. One of the promising technologies in this context is the DT model. The application of DT in construction logistics offers numerous advantages, yet the potential benefits, the adoption of DT models in the construction industry remains limited, highlighting the need for further related research and practical implementation. The research portrayed in this article aims to address this gap by employing real-time data from case studies to develop and refine DT models for construction logistics. By monitoring inventory, equipment, and transportation, DTs are expected to contribute to mitigating bottlenecks, optimizing resource allocation, enhancing efficiency, and improving resiliency and sustainability.

Future research could focus on integrating advanced analytics and machine learning into DT models to enhance predictive capabilities and explore standardized frameworks for broader adoption. Additionally, investigating DT models' impact on reducing the environmental footprint of construction logistics, including emissions tracking and resource optimization could be explored. Further studies may also assess DT's role in improving network resilience and economic implications, and conduct real-world pilot projects.

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References

1. Agarwal, R., Chandrasekaran, S., Sridhar, M.: Imagining construction's digital future. McKinsey & Company **24**(06) (2016)
2. Arayici, Y., Coates, P., et al.: A system engineering perspective to knowledge transfer: A case study approach of bim adoption. Virtual reality-human computer interaction **2006**, 179–206 (2012)
3. Bar-Cohen, A., Matin, K., Jankowski, N., Sharar, D.: Two-phase thermal ground planes: technology development and parametric results. Journal of Electronic Packaging **137**(1), 010801 (2015)
4. Barykin, S.Y., Kapustina, I.V., Kirillova, T.V., Yadykin, V.K., Konnikov, Y.A.: Economics of digital ecosystems. Journal of Open Innovation: Technology, Market, and Complexity **6**(4), 124 (2020)
5. Boje, C., Guerriero, A., Kubicki, S., Rezgui, Y.: Towards a semantic construction digital twin: Directions for future research. Automation in construction **114**, 103179 (2020)
6. Boschert, S., Rosen, R.: Digital twin—the simulation aspect. Mechatronic futures: Challenges and solutions for mechatronic systems and their designers pp. 59–74 (2016)
7. Chathuranga, S., Jayasinghe, S., Antucheviciene, J., Wickramarachchi, R., Udayanga, N., Weerakkody, W.S.: Practices driving the adoption of agile project management methodologies in the design stage of building construction projects. Buildings **13**(4), 1079 (2023)
8. Dawood, N., Akinsola, A., Hobbs, B.: Development of automated communication of system for managing site information using internet technology. Automation in construction **11**(5), 557–572 (2002)
9. Formoso, C.T., Soibelman, L., De Cesare, C., Isatto, E.L.: Material waste in building industry: main causes and prevention. Journal of construction engineering and management **128**(4), 316–325 (2002)
10. George, A.S.: 5g-enabled digital transformation: Mapping the landscape of possibilities and problems (2024)
11. Ghaffarianhoseini, A., Tookey, J., Ghaffarianhoseini, A., Naismith, N., Azhar, S., Efimova, O., Raahemifar, K.: Building information modelling (bim) uptake: Clear benefits, understanding its implementation, risks and challenges. Renewable and sustainable energy reviews **75**, 1046–1053 (2017)
12. Glaessgen, E., Stargel, D.: The digital twin paradigm for future nasa and us air force vehicles. In: 53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference 20th AIAA/ASME/AHS adaptive structures conference 14th AIAA. p. 1818 (2012)
13. Greif, T., Stein, N., Flath, C.M.: Peeking into the void: Digital twins for construction site logistics. Computers in Industry **121**, 103264 (2020)

14. Hu, W., Zhang, T., Deng, X., Liu, Z., Tan, J.: Digital twin: A state-of-the-art review of its enabling technologies, applications and challenges. Journal of Intelligent Manufacturing and Special Equipment **2**(1), 1–34 (2021)
15. Leão, C.F., Formoso, C.T., Isatto, E.L.: Integrating production and quality control with the support of information technology. In: ANNUAL CONFERENCE OF THE INTERNATIONAL GROUP FOR LEAN CONSTRUCTON. vol. 22 (2014)
16. Leviäkangas, P., Paik, S.M., Moon, S.: Keeping up with the pace of digitization: The case of the australian construction industry. Technology in Society **50**, 33–43 (2017)
17. Liu, L., Georgakis, P., Nwagboso, C.: A theoretical framework of an integrated logistics system for uk construction industry. In: 2007 IEEE International Conference on Automation and Logistics. pp. 1812–1817. IEEE (2007)
18. Makarov, D., Vahdatikhaki, F., Miller, S., Mowlaei, S., Dorée, A.: Usability assessment of compaction operator support systems using virtual prototyping. Automation in Construction **129**, 103784 (2021)
19. Marmolejo-Saucedo, J.A.: Design and development of digital twins: A case study in supply chains. Mobile Networks and Applications **25**(6), 2141–2160 (2020)
20. Musarat, M.A., Sadiq, A., Alaloul, W.S., Abdul Wahab, M.M.: A systematic review on enhancement in quality of life through digitalization in the construction industry. Sustainability **15**(1), 202 (2022)
21. Opoku, D.G.J., Perera, S., Osei-Kyei, R., Rashidi, M.: Digital twin application in the construction industry: A literature review. Journal of Building Engineering **40**, 102726 (2021)
22. Opoku, D., Perera, S., Osei-Kyei, R., Rashidi, M., Famakinwa, T., Bamdad, K.: Drivers for digital twin adoption in the construction industry: A systematic literature review. buildings 2022, 12, 113 (2022)
23. Peffers, K., Tuunanen, T., Rothenberger, M.A., Chatterjee, S.: A design science research methodology for information systems research. Journal of management information systems **24**(3), 45–77 (2007)
24. Samuelson, O., Stehn, L.: Digital transformation in construction–a review. Journal of Information Technology in Construction (ITcon) **28**, 385–404 (2023)
25. Sarkar, B.D., Shankar, R.: Understanding the barriers of port logistics for effective operation in the industry 4.0 era: Data-driven decision making. International Journal of Information Management Data Insights **1**(2), 100031 (2021)
26. Shen, W., Hao, Q., Mak, H., Neelamkavil, J., Xie, H., Dickinson, J., Thomas, R., Pardasani, A., Xue, H.: Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review. Advanced engineering informatics **24**(2), 196–207 (2010)
27. Siebert, M.: Applying a Systems Thinking Approach to the Construction Industry. Taylor & Francis (2023)
28. Turk, Ž.: Structured analysis of ict adoption in the european construction industry. International Journal of Construction Management **23**(5), 756–762 (2023)
29. Vitente, L.S., Ong, A.K.S., German, J.D.: Assessment of adoption and acceptance of building information modeling for building construction among industries in qatar. Buildings **14**(5), 1433 (2024)
30. Xu, J.: Managing digital enterprise: ten essential topics. Springer (2014)
31. Xue, X., Li, X., Shen, Q., Wang, Y.: An agent-based framework for supply chain coordination in construction. Automation in construction **14**(3), 413–430 (2005)
32. Zainal Abidin, N.A., Ingirige, B.: The dynamics of vulnerabilities and capabilities in improving resilience within malaysian construction supply chain. Construction Innovation **18**(4), 412–432 (2018)