Owais, O. A., Poshdar, M., Bidhendi, A., Jaafar, K. & Sarhan, S. (2024). From concept to concrete: Digital Twins enabling different levels of lean construction. In D. B. Costa, F. Drevland & L. Florez-Perez (Eds.), *Proceedings of the 32nd Annual Conference of the International Group for Lean Construction* (IGLC32) (pp. 767–779). doi.org/10.24928/2024/0206

FROM CONCEPT TO CONCRETE: DIGITAL TWINS ENABLING DIFFERENT LEVELS OF LEAN CONSTRUCTION

Omar A. Owais[1], Mani Poshdar[2], Ali Bidhendi[3], Kamal Jaafar[4] and Saad Sarhan[5]

ABSTRACT

The integration of Digital Twins (DTs) in Lean Construction (LC) represents a transformative approach to enhance collaboration, efficiency, waste reduction, and decision-making in construction projects. This paper explores the potential of DTs across different levels of LC through a comparative analysis method, aiming to establish a robust implementation foundation for lean organisations. Firstly, at the philosophy level, DTs foster collaboration, transparency, and respect for people by providing real-time data and virtual representations. They enable value maximisation, waste minimisation, and continuous improvement through visualisation, simulation, and data-driven decision-making. Besides, continuous improvement through monitoring and feedback loop. Secondly, at the principles level, DTs align closely with key LC principles such as value maximisation, continuous improvement, waste elimination, pull planning, continuous flow, and fast switch-over. By optimising processes, enhancing monitoring capabilities, and facilitating collaboration, DTs contribute to efficient project delivery. Thirdly, at the methods level, DTs complement LC methods such as Error Proofing, Value Stream Mapping, Target Value Design, and Last Planner System by facilitating real-time collaboration, visualising workflows, engaging stakeholders early, and providing error prevention capabilities. Overall, the strategic integration of DTs and LC thinking leads to improved project efficiency and value delivery, fostering ongoing innovation and improvement in the construction sector.

KEYWORDS

Lean construction (LC), Digital Twin (DT), Philosophy, Principles, Methods.

INTRODUCTION

In the ever-evolving landscape of construction, digital technologies integration has become a cornerstone for achieving efficiency, reducing waste, and ensuring optimal project outcomes (Tuhaise et al., 2023). One such revolutionary technology is the concept of Digital Twin (DT). It can be defined as an emerged transformative technology, offering a virtual replica of physical objects, systems, or processes (Maksimović, 2023). This means constructing a virtual duplicate

[1] Department of Built Environment Engineering, School of Future Environments, Auckland University of Technology, Auckland, New Zealand, omar.owais@aut.ac.nz, orcid.org/0000-0002-0788-3008

[2] Department of Built Environment Engineering, School of Future Environments, Auckland University of Technology, Auckland, New Zealand, mani.poshdar@aut.ac.nz, orcid.org/0000-0001-9132-2985

[3] Department of Built Environment Engineering, School of Future Environments, Auckland University of Technology, Auckland, New Zealand, ali.bidhendi@autuni.ac.nz, orcid.org/0000-0002-8285-5859

[4] Faculty of Engineering and Information Sciences, University of Wollongong, Dubai, United Arab Emirates, KamalJaafar@uowdubai.ac.ae, orcid.org/0000-0001-9134-6215

[5] School of Engineering, University of Birmingham Dubai, United Arab Emirates, s.sarhan@bham.ac.uk, orcid.org/0000-0002-0105-2350

of a physical asset or process, to enable ongoing monitoring, data analysis, and simulation of diverse scenarios. Its applicability spans various sectors, including manufacturing, construction, and the oil and gas industry (Ferrigno & Barsola, 2023).

On the one hand, DTs have significantly lowered the development cost of new manufacturing methods, enhanced efficiency, decreased waste, and minimised batch-to-batch variability (Attaran et al., 2023). On the other hand, DT has emerged in the construction sector to introduce innovative methods of controlling production during projects (Sacks et al., 2020). It combines information from a range of onsite monitoring technological equipment to offer precise and up-to-date information for effectively evaluating and enhancing the entire project process outcome. According to Sacks et al., this can be achieved through the integration of Building Information Modelling (BIM) technology, Artificial Intelligence (AI) functions, DT concepts, and lean construction (LC) thinking to create a data-centric approach to construction management aiming to enhance the overall construction sector. For instance, the integration of these technologies has the capacity to facilitate decision-making and operational processes for general contractors throughout all phases of construction. This leads to several advantages, including cost reduction, improvement in collaboration, efficient information exchange, and the implementation of construction management practices driven by data (Lv et al., 2022).

In the construction sector, DT aims to achieve several objectives. Firstly, it offers live information and evaluation of physical assets, enhancing building design, construction, and performance in architecture, engineering, and construction (AEC) sectors (Nguyen & Adhikari, 2023). Secondly, it facilitates the evaluation of potential business models by utilising stored data, aiding decision-making for future innovations (van der Veen et al., 2023). Thirdly, a DT holds the potential to revolutionise various areas in construction, including virtual design, project planning, asset management, safety, energy efficiency, structural health monitoring, sustainability, quality control, supply chain management (Omrany et al., 2023). Fourthly, its integration in construction offers benefits like improved project management, reduced errors, increased productivity, despite challenges such as initial costs and data management (Nalioğlu et al., 2023). Additionally, DTs synergise with LC, fostering collaborative efforts and aiding in the identification of benefits, costs, opportunities, and risks in LC projects.

Lean Construction (LC) is a methodology designed to reduce time, efforts, and waste of resources while optimising value in production systems (Koskela et al., 2002). It focuses on efficiency, collaboration, and waste reduction across four levels: philosophy, principles, methods, and tools and implementation (Do, 2022). Firstly, philosophy establishes foundational principles of LC incorporating “respect for people, maximising value while minimising waste, and continuous improvement”. Focusing on philosophy initially establishes the fundamental “WHY” of the lean journey. Secondly, the principles constitute the “HOW” concepts, encompassing timeless ideas such as Visual Management, Continuous Flow, Kanban, Fast switch over, Takt, Poka-yoke, etc. Thirdly, method such as Takt Planning, Set-Based Design, Last Planner System (LPS), Target Value Delivery (TVD), Choosing by Advantages, among others, guide LC implementation. Finally, these methods are applied in real-world settings using Lean tools or implementations, categorised as hybrid, analogy, or digital.

Therefore, LC aims to enhance time, cost, and resource management in construction projects by minimising waste, improving communication, and fostering collaboration (Altan & Işık, 2023; Oke et al., 2021). The adoption of LC practices has shown benefits, such as shortened project durations, reduced costs, and optimised resource allocation (Barkokebas et al., 2023). However, Do (2022) emphasised on aligning the three fundamental levels (philosophy, principles, and methods) during LC implementation, a crucial aspect often overlooked by many lean organisations. Moreover, DT is emerging as a transformative technology in construction, aiming to provide real-time data and analysis of physical assets, support decision-making, revolutionise the industry, advance processes, and interact with the LC concept. Therefore, the combination of lean principles and technological innovation might be a powerful tool for reducing waste and uncertainty in the construction operational process (Owais et al., 2023; Sacks et al., 2020).

Problem Statement: Despite its potential, the implementation of DT in construction has not been sufficiently addressed through different levels of lean thinking to establish a robust implementation foundation for lean organisations. Therefore, the aim of this research is to explore how DTs complement various levels of applying lean thinking to achieve their objectives. This investigation encompasses both conceptual and concrete dimensions. Conceptually, the study delves into the foundational philosophy, principles, and methods of DTs and LC, elucidating their collaborative potential in enhancing project efficiency and value delivery. At the concrete level, the research investigates the real-world applications of DTs and LC methodologies, aiming to bridge the future gap between theoretical frameworks and tangible outcomes in the construction sector. Through this comparative analysis, the research endeavours to establish a robust implementation foundation for lean organisations seeking to leverage DTs for optimised construction project management.

RESEARCH METHOD

This study employs a comparative analysis method to explore the integration of DTs into LC thinking. Comparative analysis plays a crucial role in theory development across various fields of research by enabling researchers to compare multiple units of study, identify correlations, and draw meaningful conclusions (Devi, 2023). The following steps have been carefully elaborated to explore the integration of DTs into LC thinking:

1. Data Collection:

- Literature Review (LR): A comprehensive LR was conducted to understand the current advancements in LC levels and DTs. Using specific search parameters such as “Lean Construction,” “Philosophy,” “Principles,” “Methods,” and “Digital Twins” on Google Scholar, journals, conferences, and books, a pool of 148 articles from 2016 onwards was identified. Subsequently, the research team analysed and curated articles focusing on LC levels and DTs, resulting in a final set of 18 articles for detailed examination.

2. Data Analysis:

- Comparative Approach: A structured comparative approach was developed to analyse the alignment between DTs and LC across different levels. This approach enables the systematic evaluation of similarities, differences, and synergies between DTs and LC.
- Categorisation: Data from the LR were categorised based on key themes and concepts related to DTs and LC levels, facilitating a deeper understanding.
- Cross-Comparison: Data from various sources were cross-compared to identify common patterns, trends, and implications, allowing for the synthesis of overarching insights.

3. Findings Interpretation:

- Synthesis of Results: Findings from the comparative analysis were synthesised to draw conclusions on the benefits and implications of integrating DTs into LC levels, highlighting key themes, and discussing their significance as shown in Figure 1.
- Practice Implications: Practical implications, challenges, and future research are provided to enhance construction practitioners and organisations adopting DTs within their LC frameworks, emphasising collaboration, efficiency enhancement, and value maximisation.

In summary, the comparative analysis method employed in this study offers a systematic and rigorous approach to examining the integration of DTs and LC, providing valuable insights and actionable recommendations for advancing lean practices in the construction industry.

DIGITAL TWINS ORIGIN AND CONCEPT

While the use of DT has achieved immense recognition in recent years, the idea itself is not entirely novel. Gelernter (1993) book "Mirror Worlds" introduced the concept of DT, envisioning software systems that simulate reality by integrating data from the physical world. He described DT as creating "Mirror Worlds," allowing users to interact with complex systems digitally. This early anticipation indicated DT's widespread application in diverse fields.

In 2002, Grieves' introduced the Mirrored Spaces Model (MSM) within discussions on Product Lifecycle Management (PLM), marking an unofficial presentation of the DT concept (Grieves, 2005). This model emphasised the connection between actual and virtual spaces, highlighting the importance of data exchange for understanding PLM information. In 2006, Grieves renamed the conceptual model to the 'Information Mirroring Model'(Grieves, 2009), emphasising bidirectional linking between spaces and the use of multiple virtual spaces for a single real space, fostering exploration of alternative ideas. However, practical DT applications faced challenges due to technological limitations, including low computing power, limited connectivity, and data management issues, as well as nascent machine algorithms.

In 2010, the term "Digital Twin" was publicly introduced by the National Aeronautics and Space Administration (NASA) within their collaborative technology roadmap, specifically within Technology Area 11: Modeling, Simulation, Information Technology, and Processing (Shafto et al., 2012). The idea was inspired by NASA's Apollo program, in which two identical spacecraft were constructed to allow the circumstances of one spacecraft to be mirrored during its journey (Shafto et al., 2010). The spacecraft that stayed on Earth was identical to the one that travelled in space.

Additionally, Tuegel (2012) highlighted the US Air Force's adoption of DT technology for aircraft development, repair, and forecasting, following NASA's lead. The aim was to replicate the mechanical and physical qualities of aircraft to predict signs of fatigue or cracks, thus extending their usable life. The concept of creating a digital representation of physical systems for analysis has existed for decades. This approach gained momentum in the construction sector with technological advancements, such as BIM, as observed by Nguyen and Adhikari (2023).

BIM entails creating digital models of buildings and infrastructure, continuously updated with real-time data, enabling better project visualisation and management (Nguyen & Adhikari, 2023). The integration of DTs into construction likely emerged alongside advancements in BIM technology. van der Veen et al. (2023) and Omrany et al. (2023) both note the gradual adoption of DTs in construction for enhanced project planning, design, construction, and maintenance, as part of a broader trend towards digital transformation across industries.

EVOLUTIONARY PROGRESSION OF DIGITAL TWINS IN CONSTRUCTION

Academic interest in DT technology, particularly in construction, has surged, resulting in numerous studies highlighting its benefits. Despite being in early stages, research has extensively examined DT applications, benefits, and challenges. For instance, Rasheed et al. (2020) explored the values, challenges, and enabling technologies of DTs, emphasising their potential to revolutionise industries and societal interactions. Their framework of Virtual Twin, Predictive Twin, and Twin Projection pillars offers clarity, with recommendations for collaborative efforts among stakeholders for successful implementation. Standardisation is crucial for facilitating interactions between DTs in a connected world. The authors thoroughly delve into DTs as virtual representations of physical assets driven by data and simulators, aiming to transform real-time prediction, optimisation, and decision-making processes. Recent advancements in computational pipelines, AI, and big data technologies have elevated DTs into a crucial trend across diverse applications.

Lee et al. (2021) explored merging DT and blockchain frameworks to enhance traceable data communication in construction projects. They addressed the challenge of fragmented information sharing among stakeholders by integrating a DT updated in near real-time through IoT sensors. Blockchain ensured authentication and traceability of data transactions, enhancing transparency and security. Testing in a case project confirmed the framework's ability to trace all data transactions and generate compliance statements promptly. The main contribution lies in promoting accountable information sharing, which could streamline contract execution, payments, and decision-making, fostering better collaboration among fragmented participants.

Akanmu et al. (2021) mentioned, also, DT play a pivotal role in revolutionising the construction industry by bridging the gap between physical assets and their virtual counterparts. This transformative technology, as underscored by recent research findings, enhances safety, efficiency, and real-time control in construction projects. The authors emphasises that the integration of DTs with emerging technologies such as virtual design modeling, sensing, and robotics forms the next generation of cyber-physical systems in the construction. These advanced systems not only improve workforce productivity, health, and safety but also offer substantial potential for lifecycle management of building systems and competency enhancement. Despite challenges, the adoption of DTs emerges as a critical catalyst for the industry's evolution toward enhanced automation and sustainable construction practices.

Yeung et al. (2022) explored the Digital Twin Construction (DTC) concept, a data-driven approach integrating BIM, LC, DTs, and AI in construction management. They emphasised simulation's role in DT, highlighting predictive situational awareness, data-driven continuous improvement, and future autonomous real-time production control. Barriers to simulation in DTC workflows are discussed, with proposed criteria for tool evaluation. The study underscores the empowering nature of DT in construction, enabling planners to optimise decisions based on comprehensive project status information and envisioning a future with autonomous production control systems. The research contributes to prototype simulation tool development within the BIM2TWIN project's virtual Plan-Do-Check-Act cycle.

Arsiwala et al. (2023) addressed the impact of Industry 4.0 on the construction sector, with a focus on achieving net-zero carbon emissions through the use of DTs. Focusing on existing assets, the research introduces a DT solution integrating IoT, BIM, and AI to automate monitoring and control of CO2 emissions. The study underscores BIM and IoT's significance for spatial information visualisation and introduces AI for predicting emissions. It proposes a user-friendly DT architecture, validated through a real-life case study, illustrating its potential in visualising real-time indoor air quality. The authors highlighted the broader implications, such as nationwide digitisation for policy making and emphasisse interdisciplinary collaboration for seamless data exchange standards in the construction industry.

ALIGNING DTS WITH LEAN CONSTRUCTION LEVELS

Technology has found its roots in the construction industry, aiming to revolutionise the sector. Many researchers have examined the emerging potential in construction, seeking to improve project outcomes with the aid of various technologies. Despite DT technology being in its infancy stage, this section will examine the emerging benefits and how DTs aid LC at different levels, including philosophy, principles, and methods. Moreover, Figure 1 will illustrate the integration benefits at the end of this section.

DT'S IN SUPPORTING LC PHILOSOPHY LEVEL

LC philosophy emphasises, firstly, respect for people by fostering collaboration, value-driven communication, and a positive work environment. Secondly, it focuses on maximising value while minimising waste through optimising processes to deliver quality results efficiently. Lastly, continuous improvement is considered the central point of encouraging ongoing learning, adaptation, and innovation for enhanced project outcomes and efficiency (Do, 2022). Several studies have examined the potential of DT in LC philosophy as an emerging technology that can aid construction project outcomes.

For instance, Sacks et al. (2020) conducted a study on DTC, integrating BIM, LC, and AI for data-centric production construction management. The research identified four key information and control concepts, delineating DTC's conceptual framework. They proposed a DTC information system workflow comprising information stores, processing functions, and monitoring technologies within three concentric control cycles. DTC is positioned as a comprehensive construction management approach, prioritising closed-loop control systems over traditional BIM tools. The authors stressed the importance of effective DTs in construction, highlighting challenges in collaboration, interoperability, and real-time monitoring. They advocated for a cohesive workflow for DTC planning and control across design and construction phases to achieve optimal project outcomes.

Barkokebas et al. (2023) have similarly advocated for the integration of a DT to enhance production flexibility in Offsite Construction (OSC), where building components are prefabricated and then assembled on-site. The OSC industry faces challenges in adapting to uncertainties, multiple projects, and variable market demands. The proposed DT leverages real-time data to autonomously reassign multiskilled workers, addressing the lack of flexibility in labour-intensive processes. Applying lean thinking metrics, the study quantifies improved production performance by considering waste reduction. Through simulation, various scenarios are assessed, revealing significant enhancements in reducing waiting time, production duration, and overall cost, affirming the DT's effectiveness in managing multiskilled workers in OSC.

Nevertheless, the authors of this research have meticulously examined, analysed, and explored the direct connections between the emerging benefits of DT and LC concept. In their pursuit of a robust implementation, they have focused on linking this emerging technology, specifically, with LC philosophy levels as a first step to address the research gap. This strategic linkage aims to enhance collaboration, efficiency, and construction project decision-making. By integrating DT into LC philosophy, the authors envision a culture that fosters lean philosophy foundation. This approach not only enhances project outcomes but also lays the foundation for a more streamlined and adaptive construction process, ultimately leading to more efficient and sustainable projects. The linkage is as follows:

Respect for People:

Collaboration and Communication: DTs offer a centralised platform that enables real-time access and sharing of project data among stakeholders (Lee et al., 2021). This accessibility breaks down silos between different project teams, fostering seamless collaboration. Team members can readily communicate, share insights, and coordinate efforts more effectively. By leveraging DTs, LC practices can be enhanced as the technology supports a collaborative environment that values everyone's expertise and contributions. This aligns with lean thinking, emphasising the importance of leveraging collective knowledge and skills to improve project outcomes.

Transparent Information: DTs ensure transparency by making project data readily accessible to all relevant parties (Rasheed et al., 2020). This transparency fosters open communication, ensuring stakeholders are well-informed about project developments and decisions. Transparent information sharing promotes trust among stakeholders, reducing misunderstandings or conflicts arising from incomplete or outdated information. Moreover, it enables stakeholders to contribute their perspectives to decision-making, leading to informed and consensus-driven decisions. This alignment with lean philosophy optimises project outcomes by leveraging stakeholders' collective intelligence.

Maximising Value While Minimising Waste:

Visualisation and Simulation: DTs offer a virtual representation of construction projects, enabling teams to visualise detailed project aspects before physical construction (Tuhaise et al., 2023). Through simulation capabilities, teams can explore diverse scenarios, test design alternatives, and optimise workflows. Early identification of issues and inefficiencies in the virtual environment allows proactive risk mitigation and waste reduction during actual construction. This capability aligns with lean philosophy by promoting continuous improvement and eliminating non-value-adding activities, ultimately enhancing project efficiency and value delivery.

Data-Driven Decision Making: DTs collect real-time data from sensors and IoT devices deployed across construction sites (Tuhaise et al., 2023). This data encompasses project progress, resource utilisation, environmental conditions, and equipment performance. Analysing this data provides valuable insights into construction process performance, enabling teams to identify improvement areas and make informed decisions for optimising project outcomes. Data-driven decision-making minimises waste by addressing inefficiencies, reallocating resources effectively, and optimising schedules and workflows to maximise value delivery. This approach aligns with lean philosophy, emphasising data-driven continuous improvement and waste elimination throughout the construction lifecycle.

Continuous Improvement:

Real-Time Monitoring and Analysis: DTs facilitate continuous, real-time monitoring of construction processes and performance through data collection from sensors, IoT devices, and project management systems (Omrany et al., 2023). This data encompasses key metrics such as project progress, resource utilisation, quality, and safety. Analysis of this data enables project teams to identify bottlenecks, areas for improvement, and opportunities for optimisation. Real-time monitoring empowers teams to proactively address issues, optimise workflows, and enhance project efficiency. By integrating DTs for continuous monitoring and analysis, LC projects can identify improvement opportunities and implement iterative changes, fostering continuous improvement throughout the project lifecycle.

Feedback Loop: DTs establish a constant feedback loop by continuously updating project information and providing timely insights into project performance (Rasheed et al., 2020). As data is continually updated and analysed, teams can learn from DT-generated insights and adjust processes accordingly. This feedback loop enables teams to adapt to changing conditions, address emerging issues, and implement improvements iteratively. By leveraging DT insights, project teams make data-driven decisions, continually enhancing project outcomes. This iterative approach aligns with lean philosophy, emphasising ongoing learning, adaptation, and refinement to optimise processes and deliver maximum value.

DT'S IN SUPPORTING LC PRINCIPLES LEVEL

The integration of DTs into the construction process aligns with several LC principles, which constitute the HOW concepts focusing on enhancing quality, value, and efficiency while minimising waste in construction projects. LC is a management-based approach that aims to deliver better value to owners by eliminating material, time, and effort wastage (Fennema, 2022). Several studies have explored the benefits of DTs at the LC principles level.

For example, Martinez et al. (2022) investigated how DTC influences LC principles, focusing on production planning. They identified challenges in construction decision-making, such as limited real-time data access and regulatory complexities. Using a matrix, they correlated operational decisions, freedom of action, and professional roles within the DTC framework, revealing its transformative potential. The study highlights DTC's role in optimising construction operations by improving decision-making aligned with LC principles. By enhancing situational awareness and decision-making, DTC demonstrates practical benefits for the construction sector.

Altan and Işık (2023) investigated the integration of DT within LC to manage escalating construction project complexity. They emphasised the collaborative nature of these approaches and analysed the synergies between them. The study identified significant obstacles and enablers in this integration by examining the Benefits, Costs, Opportunities, and Risks (BOCR) associated with DT adoption in LC. Altan and Işık underscored the crucial role of DT in reducing the cost of skilled labour and capitalising on waste reduction opportunities within the LC framework. Their research offers valuable insights into the potential enhancements DT can bring to LC principles, providing a foundational understanding for industry practitioners and guiding future research initiatives. The authors of this research focused on aligning the following LC prominent principles with DT, as a second step in bridging the research gap:

Value: DTs optimise construction processes, foster collaboration, and enhance project efficiency (McHugh et al., 2023), aligning directly with lean principles emphasising value maximisation and waste minimisation. By utilising DT, construction teams identify and eliminate non-value-added activities, thus improving project outcomes and customer satisfaction.

Continuous Improvement: DT implementation provides real-time monitoring and data analytics, enabling construction teams to gather insights for continuous improvement (McHugh et al., 2023), reflecting lean principles focused on refining processes for enhanced efficiency and quality. Analysing performance data from DT allows teams to identify optimisation areas and make iterative improvements over time, aligning with lean's principle of continuous improvement.

Waste Elimination: DT reduces waste by enhancing resource utilisation, planning, coordination, and decision-making throughout construction (Seppänen, 2022), which aligns with LC's aim of eliminating waste in all forms, including time, resources, and effort. Leveraging DT streamlines processes and enhances decision-making, minimising waste, and maximising efficiency, aligning with lean principles.

Pull Planning: DT's real-time monitoring and simulation support pull planning by providing updated information on construction activity status (Omrany et al., 2023). Pull planning, a key LC technique, aims to align production with customer demand. With DT, teams adjust plans based on actual demand and progress, enabling efficient resource allocation, and reducing unnecessary work, aligning with lean's pull planning principle.

Continuous Flow: DT implementation offers a centralised platform for collaboration and communication, enhancing coordination among project teams, suppliers, and stakeholders (Ferrigno & Barsola, 2023). Effective communication and teamwork are LC fundamentals, emphasising collaboration's importance for efficient project goal achievement. DT enhances collaboration and communication, aligning efforts and streamlining workflows, in line with LC principles.

Fast Switch-Over: DTs enable fast switch-over by providing live data and simulations, allowing teams to adapt quickly to project requirement changes or conditions (Jungmann et al., 2023). LC prioritises responding swiftly to changes and disruptions while maintaining project flow and efficiency. With DT, teams assess change impacts and adjust plans to minimise downtime and maintain momentum, reflecting lean principles of agility and flexibility in project execution, ultimately improving overall performance.

DT'S IN SUPPORT LC METHODS LEVEL

LC methods represent a strategic approach to streamline project delivery in the construction industry, emphasising efficiency, waste reduction, and continuous improvement. Grounded in Lean thinking principles, these methods prioritise value creation for clients while minimising resources and time (Do, 2022). They serve as the practical means to achieve LC thinking after adopting its principles, representing the final step in bridging the research gap. These methods include SCRUM, Takt Planning, Reliable Promises, Set Based Design, Choosing by Advantages, TVD, LPS, etc. LPS and TVD, specifically developed and implemented for the construction sector, were highlighted by Do. Moreover, emerging DTs as advanced technology can enhance LC methods by providing a technology-driven infrastructure that fosters collaboration, efficiency, and decision-making throughout the building lifecycle. Several studies have explored the potential of emerging DTs in LC methods.

For example, Mao et al. (2022) highlighted significant research findings on integrating DT technology into LC methods. Their meticulous review identified key constituents crucial for efficient constraint management. They explored DT's fusion with constraint management, pinpointing potential constituents. The research emphasised the importance of: (1) Information technologies like BIM, Global Positioning Systems (GPS), and Automated Data Collection (ADC) for precise constraint modelling and data traceability; (2) Swarm Intelligence and Genetic Algorithm for addressing spatial and resource constraints during construction scheduling; (3) Semantic Web technologies, particularly ontology, enabling advanced constraint modelling; and (4) Lean-based methods such as LPS, WFP, and AWP for structured constraint resolution processes. These insights provide a roadmap for leveraging DT technology to optimise LC project efficiency and productivity.

Ramirez et al. (2022) tackled slow decision-making in multi-family building projects, especially in countries like Peru, causing economic losses and inefficiencies. Their solution integrates LC 4.0 methodologies, blending DTs and visual management. A Lima case study illustrates how DTs enable detailed project analysis, remote stakeholder involvement, and enhanced decision-making in quality controls. The LC and Construction 4.0 synergy proves effective, with over 70 per cent acceptance, validating LC 4.0's technical feasibility and efficiency for improved global construction project execution and decision-making.

McHugh et al. (2023) investigated the integration of LC methods and digital tools in construction, focusing on a data centre case study. Through action research, they highlighted the LPS in establishing centralised digital command rooms. Digital tools, aligned with lean methods, enhance transparency, collaboration, and innovation. The study emphasised the importance of correct data management and skilled workers. Findings showcased how digital platforms improve communication, visibility, and collaboration, fostering a continuously improving project environment.

Recent research has underscored the emerging role of DT in LC methods. DTs provide virtual representations of physical assets and processes, aiming to revolutionise the construction industry. Within the context of LC methods, DTs hold the potential to enhance efficiency, reduce waste, and improve overall project outcomes. This discussion will explore how DTs complement prominent LC methods, drawing insights from the authors' research of this paper. Their findings emphasise the significant impact of DTs on LC methods, suggesting the potential for DTs to revolutionise traditional LC approaches, as follows:

Last Planner System (LPS): DTs enable real-time collaboration by centralising a platform for project data among stakeholders, including designers, contractors, and clients (Rasheed et al., 2020). They provide access to live project data, such as schedules, progress reports, and design iterations, fostering effective communication and decision-making. For example, a DT platform can integrate scheduling software with real-time construction site data, allowing stakeholders to monitor progress, identify bottlenecks, and adjust accordingly. Teams can use the DTs to visualise the project schedule, allocate resources effectively, and coordinate tasks among different trades. This enhances communication and coordination, ultimately improving the reliability and efficiency of the LPS.

Value Stream Mapping (VSM): Integrating DT offers visual representations of construction processes, helping teams identify non-value-added activities and optimise workflows (Tuhaise et al., 2023). For instance, DT can simulate materials, equipment's, and manpower flow, enabling teams to identify inefficiencies, such as excessive waiting times or unnecessary movement of materials and implement strategies to streamline processes. DTs with simulation capabilities can also help teams evaluate different scenarios and determine the most efficient layout or sequence of tasks to reduce lead times, aligning with VSM goals to streamline processes and eliminate waste.

Target Value Design (TVD): DTs facilitate early stakeholder engagement by providing virtual models for assessing design alternatives and their impact on cost and value (Adade & de Vries, 2023). They enable the alignment of project goals with budget constraints and client needs. For instance, architects and engineers create DTs of building designs, utilising parametric modelling to explore various configurations or materials. Stakeholders can visualise the model to evaluate the implications of design decisions on cost, schedule, and project value.

DTs promote collaborative decision-making, enabling teams to iterate on design concepts and align project goals with budget constraints from early stages, ultimately optimising project value in line with TVD principles.

Error Proofing (Poka-Yoke): DTs aid error prevention by simulating and validating construction processes before physical construction starts (Ferrigno & Barsola, 2023). Teams, for instance, can use DTs to simulate assembly sequences, equipment operation, or installation processes to identify potential errors or safety hazards. By analysing the virtual simulation, teams can proactively address issues such as clashes or structural weaknesses, minimising errors during construction. DTs offer a platform for virtual testing and validation, allowing teams to refine plans and ensure compliance with quality and safety standards, aligning with error-proofing and continuous improvement principles in LC methods.

Overall, Figure 1 below explores the outcomes of integrating DTs with different LC levels.

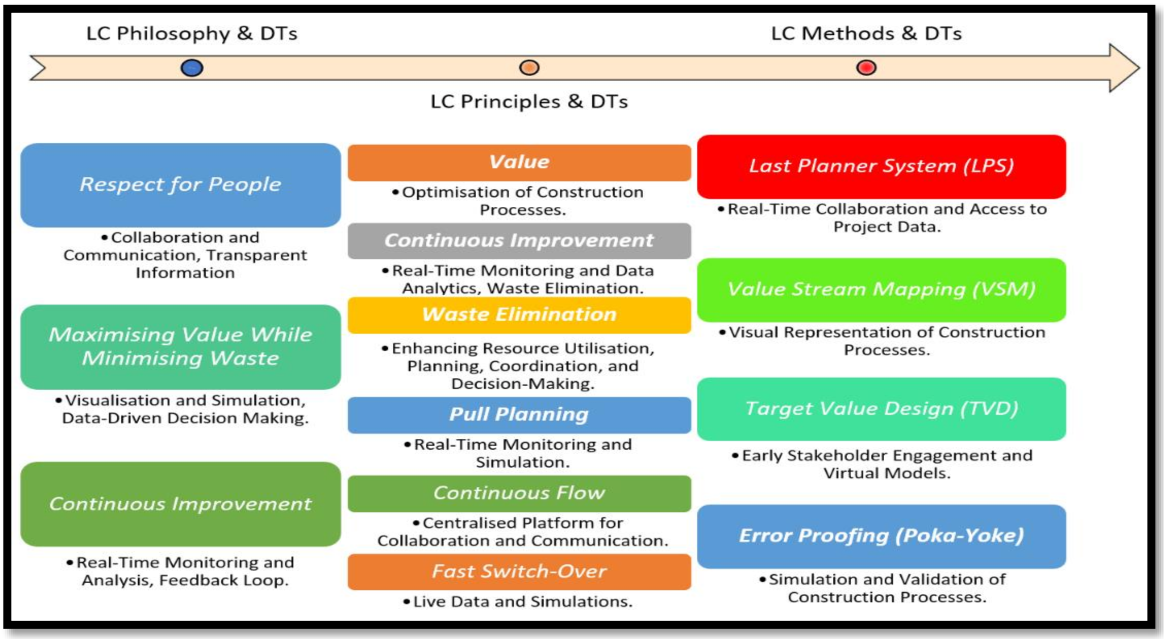

Figure 1: Benefits and Implementation of Integrating DTs into LC Levels

As a result, it is important to encompass the three identified levels of LC while integrating DTs. This is to establish a solid foundation for organisations aiming to adopt DTs within their LC frameworks, emphasising collaboration, efficiency enhancement, and value maximisation.

CONCLUSIONS

The integration of DTs into LC aims to revolutionise collaboration, efficiency, waste reduction, and decision-making in construction projects for optimal outcomes. However, DTs are still in their infancy stage and have not been sufficiently addressed across different levels of LC. Therefore, this research aims to fill the identified gap by revealing DTs' potential in supporting various levels of LC thinking, including philosophy, principles, and methods. The ultimate goal is to improve project outcomes for efficient and sustainable construction practices by establishing a solid implementation foundation for lean organisations.

At the philosophy level, DTs foster collaboration and communication among project stakeholders, promoting transparency and a culture of respect while maximising value and minimising waste through real-time data and virtual representation, aligning with the core thinking of LC through visualisation, simulation, and data-driven decision-making. As well as continues improvement through real time monitoring, analysis, and feedback loop. This philosophy extends to the principles level, where DTs closely adhere to LC principles such as value maximisation, continuous improvement, waste elimination, pull planning, continuous flow, and fast switch-over, contributing to efficient project delivery by optimising processes, enhancing monitoring capabilities, collaboration and communication, simulation, and enabling data-driven decision-making. At the methods level, DTs complement LC methods such as the LPS, VSM, TVD, and Poka-Yoke, facilitating real-time collaboration, workflow visualisation, stakeholder engagement, and error prevention, ultimately leading to enhanced project efficiency and value delivery.

Nevertheless, the integration of DTs with LC faces various challenges, including technological complexity, data privacy concerns, integration barriers, and limited industry adoption. Thus, future research endeavors should concentrate on simplifying DT solutions for the construction sector, addressing privacy and security issues, overcoming integration barriers, and exploring factors influencing adoption to unlock DT's full potential in LC.

In conclusion, integrating DTs into LC embodies a synergistic approach toward achieving lean objectives in construction projects. By harnessing DTs' capabilities to support collaboration, transparency, and data-driven decision-making, construction teams can streamline processes, reduce waste, and deliver greater value to stakeholders. This strategic integration lays the groundwork for more efficient and sustainable construction practices, fostering ongoing innovation and improvement in the industry. This conclusion is drawn from a comparative analysis method aimed at bridging the gap by revealing the linkage between DT and various LC levels.

REFERENCES

Adade, D., & de Vries, W. T. (2023). Digital Twin for Active Stakeholder Participation in Land-Use Planning. *Land*, *12*(3), 538.

Akanmu, A. A., Anumba, C. J., & Ogunseiju, O. O. (2021). Towards next generation cyber-physical systems and digital twins for construction. *Journal of Information Technology in Construction*, *26*.

Altan, E., & Işık, Z. (2023). Digital twins in lean construction: a neutrosophic AHP–BOCR analysis approach. *Engineering, Construction and Architectural Management*.

Arsiwala, A., Elghaish, F., & Zoher, M. (2023). Digital twin with Machine learning for predictive monitoring of CO2 equivalent from existing buildings. *Energy and Buildings*, *284*, 112851.

Attaran, M., Attaran, S., & Celik, B. G. (2023). The impact of digital twins on the evolution of intelligent manufacturing and Industry 4.0. *Advances in Computational Intelligence*, *3*(3), 11.

Barkokebas, B., Al-Hussein, M., & Hamzeh, F. (2023). Assessment of digital twins to reassign multiskilled workers in offsite construction based on lean thinking. *Journal of Construction Engineering and Management*, *149*(1), 04022143.

Devi, B. (2023). Application of Cross-National Comparative Research Design in Medical and Nursing Education. *Journal of Health and Allied Sciences NU*, *13*(03), 306-312.

Do, D. (2022). *The Art and Philosophy of Lean Construction*.

Fennema, L. (2022). Applying Lean Construction principles to noise mitigation design. INTER-NOISE and NOISE-CON Congress and Conference Proceedings,

Ferrigno, E., & Barsola, G. A. (2023). 3D Real Time Digital Twin. SPE Latin American and Caribbean Petroleum Engineering Conference,

Gelernter, D. (1993). *Mirror worlds: Or the day software puts the universe in a shoebox... How it will happen and what it will mean*. Oxford University Press.

Grieves, M. (2009). Back to the future: Product lifecycle management and the virtualization of product information. *Product Realization: A Comprehensive Approach*, 1-13.

Grieves, M. W. (2005). Product lifecycle management: the new paradigm for enterprises. *International Journal of Product Development*, *2*(1-2), 71-84.

Jungmann, M., Hartmann, T., Tomar, R., & Ungureanu, L. (2023). A COMBINED DIGITAL TWIN AND LOCATION-BASED MANAGEMENT SYSTEM. https://doi.org/doi.org/10.24928/2023/0184

Koskela, L., Howell, G., Ballard, G., & Tommelein, I. (2002). The Foundations of Lean Construction. Design and Construction: Building in Value, R. Best, and G. de Valence, eds. In: Butterworth-Heinemann, Elsevier, Oxford, UK.

Lee, D., Lee, S. H., Masoud, N., Krishnan, M., & Li, V. C. (2021). Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. *Automation in construction*, *127*, 103688.

Lv, Z., Ota, K., Lloret, J., Xiang, W., & Bellavista, P. (2022). Complexity problems handled by advanced computer simulation technology in smart cities 2021. In (Vol. 2022): Hindawi.

Maksimović, M. (2023). A faster path to sustainability: the use of Digital Twins. 2023 22nd International Symposium INFOTEH-JAHORINA (INFOTEH),

Mao, Z., Gonzalez, V. A., & Zou, Y. (2022). Exploring a Digital Twin Framework for lean management of constraints in construction: A literature review. IOP Conference Series: Earth and Environmental Science,

Martinez, J. G., Yeung, T., & Sacks, R. (2022). Production Planners' Scope of Action in the Context of Digital Twin Construction. Construction in the 21st Century 12th International Conference (CITC 12),

McHugh, K., Dave, B., & Bolpagni, M. (2023). THE ROLE OF LEAN IN DIGITAL PROJECT DELIVERY. https://doi.org/doi.org/10.24928/2023/0214

Nalioğlu, V., Tokdemir, H., & Artan, D. (2023). Adopting Digital Twin and Internet of Things in the Construction Industry: A SWOT Analysis. International Symposium of the International Federation for Structural Concrete,

Nguyen, T. D., & Adhikari, S. (2023). The role of bim in integrating digital twin in building construction: A literature review. *Sustainability*, *15*(13), 10462.

Oke, A., Akinradewo, O., Aigbavboa, C., & Ndalamba, M. (2021). Challenges to the Implementation of Lean Construction Practices in the South African Construction Industry. Collaboration and Integration in Construction, Engineering, Management and Technology: Proceedings of the 11th International Conference on Construction in the 21st Century, London 2019,

Omrany, H., Al-Obaidi, K. M., Husain, A., & Ghaffarianhoseini, A. (2023). Digital twins in the construction industry: a comprehensive review of current implementations, enabling technologies, and future directions. *Sustainability*, *15*(14), 10908.

Owais, O. A., Poshdar, M., GhaffarianHoseini, A., & Ghaffarianhoseini, A. (2023). LEAN CONSTRUCTION WASTE REDUCTION THROUGH THE AUTONOMOUS VEHICLE TECHNOLOGY. *31st Annual Conference of the International Group for Lean Construction (IGLC 31)*. https://doi.org/10.24928/2023/0222

Ramirez, N. L., Del Valle, C. M., & Salazar, J. D. L. T. (2022). Feasibility of the implementation of Lean Construction 4.0 in multi-family projects to improve the decision-making experience using digital twin. 2022 Congreso Internacional de Innovación y Tendencias en Ingeniería (CONIITI),

Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital twin: Values, challenges and enablers from a modeling perspective. *Ieee Access*, *8*, 21980-22012.

Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. (2020). Construction with digital twin information systems. *Data-Centric Engineering*, *1*, e14.

Seppänen, O. (2022). Use of the Digital Situation Picture to Decrease Waste in the Design and Construction Process. In *Lean Construction 4.0* (pp. 240-253). Routledge.

Shafto, M., Conroy, M., Doyle, R., Glaessgen, E., Kemp, C., LeMoigne, J., & Wang, L. (2010). Draft modeling, simulation, information technology & processing roadmap. *Technology area*, *11*, 1-32.

Shafto, M., Conroy, M., Doyle, R., Glaessgen, E., Kemp, C., LeMoigne, J., & Wang, L. (2012). Nasa technology roadmap: Modeling, simulation. *Information Technology & Processing Roadmap Technology Area*, *11*.

Tuegel, E. (2012). The airframe digital twin: some challenges to realization. 53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference 20th AIAA/ASME/AHS adaptive structures conference 14th AIAA,

Tuhaise, V. V., Tah, J. H. M., & Abanda, F. H. (2023). Technologies for digital twin applications in construction. *Automation in Construction*, *152*, 104931.

van der Veen, S., Meusburger, E. B., & Meusburger, M. (2023). Digital twin as enabler of business model innovation for infrastructure construction projects. ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction,

Yeung, T., Martinez, J., Sharoni, L., & Sacks, R. (2022). The role of simulation in digital twin construction. Proceedings of the 29th EG-ICE international workshop on intelligent computing in engineering, (pp. 248-258).