Ramirez, J. M., Iordanova, I. (2025). Analysis of the integration between Digital Twins and Lean Construction for construction projects. In O. Seppänen, L. Koskela, & K. Murata (Eds.), *Proceedings of the 33rd Annual Conference of the International Group for Lean Construction* (IGLC33) (pp. 941-952)..https://doi.org/10.24928/2025/0288

ANALYSIS OF THE INTEGRATION BETWEEN DIGITAL TWINS AND LEAN CONSTRUCTION FOR CONSTRUCTION PROJECTS

Jorge Mauricio Ramirez[1] and Ivanka Iordanova[2]

ABSTRACT

In recent years, academics and stakeholders in the Architecture, Engineering and Construction (AEC) industry have developed strategies to address the issue of low productivity, resulting in the emergence of two distinct approaches: the 'managerial' and the 'technological'. Recently, researchers have advocated the integration of these approaches, in particular by exploring the potential for an integrated implementation of the Digital Twin (DT) concept and Lean Construction (LC) theory. In order to contribute to the theoretical foundation of this integration, this study investigates the theoretical feasibility of an integration between DT and LC in the context of construction projects by adopting a mixed methods research approach, combining literature review with a hybrid analytical approach. The following general research question is addressed: "Is a synergy between the DT concept and the LC theory feasible and beneficial in the context of construction projects? If 'yes', in what contexts and how?" As a novelty, this study explores possible interactions between the principles, functionalities, potentials, barriers and challenges of both DT and LC in order to theorize the positive and negative aspects of this integration in the context of construction projects. Preliminary results show that some of the barriers that prevent the full use of LC in the execution of construction projects can be overcome if its implementation is supported by a technological application based on the concept of DT. In turn, a DT application can add value to the process and the final product, thus addressing some of the challenges to its wider adoption in the construction phase of AEC projects.

KEYWORDS

Lean construction (LC), Digital Twin (DT), DT-LC integration, construction productivity.

INTRODUCTION

Construction projects struggle with high levels of customization, short lead times, cost pressures and inadequate planning and control, resulting in low levels of productivity (Schulze & Dallasega, 2020). For years, academics and practitioners have sought to improve productivity through two main approaches. The first approach focuses on the development of "managerial" theories, methods, and tools aimed at optimizing resource allocation, planning, and control in construction. Within this, Lean Construction (LC) theory (Koskela et al., 2002) has been one of the most widely developed and implemented strategies, thanks to its ability to address the root causes of low productivity in AEC projects (Schulze & Dallasega, 2020), but significant barriers and challenges limit its effectiveness and adoption. The second approach is the 'technological' one, which focuses, among other things, on developing solutions to digitize

[1] PhD Candidate, Département de génie de la construction, École de technologie supérieure, Université du Québec, Canada, jorge-mauricio.ramirez-velasquez.1@ens.etsmtl.ca, orcid.org/0009-0009-0332-6042

[2] Professor, Département de génie de la construction, École de technologie supérieure, Université du Québec, Canada, ivanka.iordanova@etsmtl.ca, orcid.org/0000-0002-4596-2604

project activities and automate the use of information. Within this context, the digital twin (DT) concept (Grieves & Vickers, 2017) has garnered the interest of many researchers due to its potential to create virtual replicas of dynamically connected physical entities. However, the misinterpretation of this concept and the lack of awareness of its value hinder its wider adoption for construction activities. To date, despite the development and implementation of solutions in both approaches, productivity gains have lagged behind other industries. For example, McKinsey (2024) found that productivity in construction increased by 10% between 2000 and 2022, while the economy as a whole has grown by 50% and manufacturing by 90% over the same period.

Motivated by the idea that LC and DT share similar goals, academics and practitioners have recently proposed exploring forms of integrating DT and LC in construction, but an exploratory literature review identified a lack of theoretical and analytical evaluation of the implications of such an integration. Therefore, this study attempts to fill this gap by addressing the general research question (GRQ): *"Is a synergy between the DT concept and the LC theory feasible and beneficial in the context of construction projects?"*. The motivation for this paper is to contribute to the theoretical foundation of LC and DT integration and to encourage academia and AEC industry stakeholders to develop practical applications that integrate both concepts and then evaluate their effectiveness in improving industry productivity. This study adopts a mixed methods research approach, combining literature review methods with a hybrid analysis to answer the above-mentioned GRQ.

The paper is organized as follows: First, the results of the literature review are presented. This includes a theoretical overview of LC theory, focusing on barriers and challenges to its implementation, the key aspects of the DT concept, including challenges to its adoption, and an overview of the integration of LC and digital tools. The second section describes key aspects of the methodology used in this study. The third section proposes and evaluates three analysis scenarios of DT-LC integration by developing a specific research question (SRQ) derived from the GRQ. The fourth section presents the main findings of this study. Finally, the last section presents limitations and recommendations for future research.

THEORETICAL BACKGROUND

LEAN CONSTRUCTION

LC is a theory that addresses low performance issues in construction by providing a theoretical basis for reformulating production processes (Koskela et al., 2002). It introduces a set of principles, methods and tools aimed at improving the flow of the production process, increasing the value of its activities and identifying and minimizing waste (Koskela et al., 2002). It applies and adapts the concepts and principles of the Toyota Production System (TPS) to construction (Dave et al., 2016). Despite its attractiveness and not insignificant implementation in construction projects, several barriers hinder its wider adoption. For example, Schulze and Dallasega (2023) identified several barriers in the context of construction companies and proposed their categorization into six groups as follows: organization, management, knowledge, culture, finance, customer and non-context specific. Additional studies on other specific contexts and regions have also identified them, such as Sarhan et al. (2018) in the construction sector of Saudi Arabia, Prabaharan and Shanmugapriya (2023) in the Indian context, and Tezel et al. (2018) in the UK highway construction sector.

Integration of LC with Industry 4.0 (I4.0) technologies

In the manufacturing sector, the integration of Lean and I4.0 to improve productivity has been discussed. For example, Mayr et al. (2018) studied the interaction between I4.0 and Lean Management (LM). Their findings show three trends: in the first, LM is seen as a prerequisite for the adoption of I4.0; in the second, I4.0 is seen as an enabler of LM; in the third, this integration creates positive synergies. Learning from improvements in manufacturing and given the growing adoption of I4.0 technologies in construction, practitioners and researchers have explored ways to integrate theories such as LM with some I4.0 technologies such as Building Information Modelling (BIM), Internet of Things (IoT) or even DT (Dave et al., 2016; Hamzeh et al., 2021; Schulze & Dallasega, 2020; Sepasgozar et al., 2021).

THE DIGITAL TWIN CONCEPT

The original idea behind the concept of a DT envisioned a manufacturing system represented by two interconnected entities: one, a real, tangible or physical entity, and the other, a virtual replica or twin that contains rich information about the real system (Grieves & Vickers, 2017). However, as DT has evolved rapidly from a theoretical concept to an attractive and adopted technology, each industry and research domain has adapted its understanding and definition to its own purposes, leading to a wide range of interpretations (Callcut et al., 2021) and overlapping with other concepts such as Cyber-Physical Systems (CPS) (Jiang et al., 2021) and BIM (Naderi & Shojaei, 2023).

DT Components and Capabilities

In the original architecture of DT, it consisted of three parts: a physical entity, a virtual entity, and connections between the two (Grieves & Vickers, 2017). Then, Qi and Tao (2018) proposed adding to it "data" and "services". In this, data acts as a provider of its intelligence and services as a determinant of its purpose and its technical abilities. However, due to the lack of standardization, DT's abilities change from one application to another. In the AEC industry, Boje et al. (2020) identified sensing, monitoring, acting, simulating, predicting, optimizing and acting as key capabilities of DTs. In addition, by integrating big data technologies, DTs are able to process large amounts of data, facilitating the integration of asset lifecycle data (Qi & Tao, 2018). In terms of integrated technologies, they can serve as a common data environment (CDE) where I4.0 technologies (also known as digital twin technologies - DTT) converge. In the context of infrastructure projects, Naderi and Shojaei (2023) identified four technological components that form the backbone of DTs applications as follows: information model technologies (IMT), data acquisition technologies (DAT), data processing technologies (DPT), and interoperability solutions. Technologies such as BIM, GIS and Simulation Models (SM) are preferred for IMT, LiDAR Unmanned Aerial Vehicle (UAV) and Radio Frequency Identification (RFID) - as DAT, Machine Learning (ML) and Computer Vision (CV) - as DPT, and Industry Foundation Classes (IFC) data formats, Sensor Model Language (SensorML) and semantic technologies as interoperability facilitators.

Applications and challenges for DT in construction

In the AEC industry, DT applications appear to be concentrated in the operation and maintenance (O&M) phase, and in a much-limited scope in the construction phases (Akanmu et al., 2021; Jiang et al., 2021). The applications are mostly single-purpose and single-phase (Callcut et al., 2021). According to Akanmu et al. (2021), one of the main objectives of a DT is to facilitate communication and coordination between the virtual entity and the "physical construction/built facility". In terms of specific purposes, site logistics, position tracking and control, facility management, preventive maintenance and building performance assessment were identified by (Akanmu et al., 2021), while site progress monitoring, real-time data visualization and safety detection were identified by (Boje et al., 2020). As with LC, the implementation of the DT concept in construction faces numerous challenges. On the one hand, due to its nascent implementation, the literature notes the lack of a unified definition, standards and regulations, as well as a lack of technical expertise (Jiang et al., 2021; Singh et al., 2021). These factors limit the maturity of DT applications, resulting in low awareness. However, to increase the value of DTs, some authors suggest their use to support management functions as the supply chain integration (Akanmu et al., 2021; Sacks et al., 2020), avoiding their implementation from a purely technological perspective (Singh et al., 2021). On the other hand, the complexity of developing DTs (Jiang et al., 2021), in addition to interoperability issues, and the siloed implementation of digital tools in construction (Akanmu et al., 2021; Sacks et al., 2020; Singh et al., 2021) have made rapid adoption difficult. Finally, the literature also points to the need for high investment and the high perception of risk in the development of DTs as additional aspects that may hinder their uptake (Singh et al., 2021).

LEAN CONSTRUCTION AND DIGITAL TOOLS INTEGRATION

Regarding the integration of LC with digital tools, Sepasgozar et al. (2021) observed a transition in LC over the last decade from a theory-based implementation to a more practical one supported by technology. This study highlights the role of digital tools in the collection and visualization of data, especially in the case of BIM. In line with this, significant examples of the integration of I4.0 technologies with LC practices were found in the literature, such as VisiLean, which combines BIM, Last Planner System (LPS) and cloud computing (Dave, 2013), and KanBIM, which integrates BIM and LC tools as LPS and Kanban (Sacks et al., 2013).

In terms of DTs, previous works have proposed and explored theoretical possibilities to integrate DT applications to improve LC implementation. For Sepasgozar et al. (2021), future research should focus not only on investigating the pros and cons of models where sensors and IoT technologies collect and feed data into BIM systems to support lean strategies, but also on identifying constraints as a critical factor to enhance construction productivity. Hamzeh et al. (2021) emphasize the need for LC to embrace I4.0 in order to continue to evolve and remain relevant to the AEC industry. Sacks et al. (2020) formulated the concept of the 'Construction Digital Twin' (CDT) as an information system capable of monitoring and controlling workflows through a 'data-centric mode of management', enabling a ‘more comprehensive form of planning and control for projects' by combining BIM, LC, AI and DAT. Recently, Altan & Işık (2023) developed a study to assess the benefits, opportunities, costs and risks (BOCR) associated with the adoption of DT for LC. As key findings, they outline improved visualization and proactivity as the main benefits, while waste reduction and process innovation and improved optimization as the main opportunities. At the same time, the risk associated with the appropriate choice of DT technologies and the reliance on skilled training were identified as challenging aspects. Finally, system components and skilled labour were identified as factors influencing the cost of DT implementation (Altan & Işık, 2023).

METHODOLOGY

This research adopts a mixed methods approach to answer the proposed research question. It is structured into two main phases combining systematic literature reviews (SLRs) with hybrid analysis. In the first stage, two literature reviews were conducted. The first was exploratory and aimed to identify future directions for DTs in construction. The second followed an SLR protocol, focusing on the question of "challenges and barriers to LC implementation" and "challenges and future trends related to DTs in construction". Both reviews incorporated backward and forward snowballing techniques and were conducted using the Scopus and Web of Science databases. The results revealed a lack of theoretical and analytical evaluations of the integration between DT and LC - highlighting the identified research gap. In the second phase, in order to address the interdisciplinary nature and complexity of the issue, a hybrid analytical approach was adopted, combining: Conceptual analysis, to explore the theoretical compatibility between DT and LC principles; Comparative analysis, to identify mutual benefits, especially in overcoming adoption barriers and challenges; and Feasibility analysis, to assess the practical alignment between DT implementations (case studies) and LC principles in construction project environments.

CONCEPTUAL ANALYSIS OF DT-LC INTEGRATION

This study focuses on the execution phase of construction projects, where DT and LC are implemented in an integrated manner. In this context, LC serves as a theoretical basis for improving construction processes by identifying sources of waste and prescribing appropriate tools and techniques based on LC thinking. In turn, a DT application is used with the main objective of collecting, processing and visualizing the information required by LC practices. In other words, *LC defines the purpose and information needs of the DT application, while DT supports the effective management of this information to facilitate LC implementation*. To address the GRQ, three specific research questions (SRQs) are derived and analyzed in the following parts of this document, with each SRQ forming an analysis scenario in its own subsection. The results of these analyses are based on the literature review as described in the previous sections.

SRQ1 - CAN DTS HELP OVERCOME THE BARRIERS TO IMPLEMENTING LC?

In this sub-section, through a comparative analysis, we address SRQ1 by assessing the impacts that the application of DT would have on the implementation of LC, in particular by analyzing whether DT can contribute to overcoming some of the LC barriers identified in the literature review. Initially, 67 barriers were identified, and after eliminating duplicates, we focused on barriers that could be directly impacted by DT. This process resulted in a total of 10 barriers, which were then grouped into technical/technological (Table 1) and organizational/cultural (Table 2) categories. Then, based on the findings from the literature an assessment of the impact that a DT -supporting technologically LC implementation- could have on each of the selected barriers was performed. In Table 1 and Table 2, the impact on LC barriers is qualified as (+++) for positive, (-0+) for neutral and (---) for negative.

Table 1: Analysis of the impact of DT over LC technical and technological barriers.

LC Technical/Technological barriers*	Assessment of the impact
Insufficient or inadequate resources for information management (Ref. 1) Lack of or insufficient measurement system (metrics, indicators, benefits) (Ref. 3)	(+++) Given the ability of DT to manage large amounts of data (Jiang et al., 2021; Qi & Tao, 2018), a DT can improve information management and facilitate the collection of LC metrics and indicators. Similar to (Dave et al., 2016), a DT can support LC practices to obtain timely and accurate production control information.
Lack of technological adaptation or facilities (Ref. 2)	(+++) By acting as a CDE, a DT can integrate data and make it accessible and visualizable through user-friendly environments such as dashboards. Peng et al. (2020) developed a DT to integrate technical, managerial, and lifecycle information to facilitate project management.
Fragmented implementation (limited to some LC aspects or tools) (Ref. 1) Insufficient know-how about LC (Ref. 1; Ref. 2; Ref. 4) Low awareness about LC techniques & concepts (Ref. 4)	(+++) Given its technical capabilities to manage information, a DT could support the implementation of different LC tools simultaneously (Boje et al., 2020; Qi & Tao, 2018). (-0+) Given that a DT-based solution is usually single-purpose (Callcut et al., 2021), it might not contribute to the dissemination of the LC thinking, or to the increase of knowledge about its techniques.

* Ref. 1 refers to (Schulze & Dallasega, 2023), Ref. 2 to (Sarhan et al., 2018), Ref. 3 to (Tezel et al., 2018), Ref.4 to (Prabaharan & Shanmugapriya, 2023).

Table 2: Analysis of the impact of DT over LC organizational and cultural barriers.

LC Organizational/Cultural barriers*	Assessment of the impact
Lack of planning, coordination, communication and collaboration between stakeholders for LC implementation (Ref. 2; Ref. 3) Inadequate or lack of customer support or involvement (Ref. 2)	(+++) A DT solution can improve communication between stakeholders *(including customers and the supply chain)* by improving the quality and quantity of project information exchanged. For example, (Peng et al., 2020) noted a 10% increase in management satisfaction compared to a previous clinical building project.
Financial risk aversion or perception of non-financial advantage (Ref. 1; Ref. 2) Perception of high or additional costs involved in LC implementation (Ref. 1; Ref. 2; Ref. 3)	(+++) The implementation of a LC-based DT application focused on identifying and eliminating "waste" can improve the performance of the production process and thus increase the "value" (Dave et al., 2016). This, in turn, can generate positive returns, mitigate investment aversion and raise awareness of LC.

SRQ2 - Can the Integration with LC enhance the Value of DT?

In this sub-section, we address the implications for barriers and challenges to the implementation of DTs in construction, when DT's purpose is driven by a LC thinking. The results of the analysis are presented in Table 3. In this, relevant barriers and challenges were identified in the literature and then filter out depending on the potential direct impact that LC thinking could have on them. Subsequently, the type of impact that LC-defining the purpose of the DT application- could have on each selected barrier or challenge, was assessed as: (+++) positive; (-0+) neutral or (---) negative, based on the analysis of literature findings.

Table 3: Assessment of impacts on DT challenges thanks to integration with LC thinking

DT aspect	Assessment of the impact of joint implementation with LC
Awareness about its value. (Singh et al., 2021)	(+++) Due to the alignment of their goals -improving construction productivity - and their mutual ability to support the production process, a DT-LC integration can improve planning (Sheikhkhoshkar et al., 2024) and control capabilities (Dave et al., 2016), thus, increasing the value and awareness of DTs in the construction context (Sacks et al., 2020).
Adoption of DTs beyond a technological perspective. (Singh et al., 2021)	(+++) The DT implementation could involve disciplines such as management and supply chain (Sacks et al., 2020), thus avoiding their adoption being merely a new trend. Since LC is recognized as one of the "best practices" in management, integrating LC to guide the purpose of DT can enhance the benefits of DT.
Integration and support to supply chain. (Sacks et al., 2020)	(+++) With the technical capabilities to collect, process, and visualize data, a DT can support the integration of the entire construction supply chain. For example, guided by LC tools such as Just-In-Time (JIT) and LPS.
Interoperability issues (Akanmu et al., 2021)	(---) Traditional silo working, together with the plethora of technological solutions available in AEC industry (Sacks et al., 2020), can make DT implementation difficult. However, a technological tools based on the logic of LC thinking as proposed by (Dave, 2013), could employ technological solutions to improve interoperability (Naderi & Shojaei, 2023).
Perception of not positive benefits of DT implementation in the construction phase. (Singh et al., 2021)	(+++) To demonstrate the value of DTs, some authors suggest focusing on practical applications, such as supporting management tasks, monitor work performance and improving supply chain's integration (Akanmu et al., 2021; Sacks et al., 2020; Singh et al., 2021). The potential to improve progress monitoring and control through the theorical guidance of LC can increase the value and perceived benefits for DTs in construction projects.

SRQ3 - WHAT IS THE IMPACT OF THE INTERACTION BETWEEN LC PRINCIPLES AND DT FUNCTIONALITIES IN CONSTRUCTION?

In this sub-section, a practical feasibility analysis was carried out to determine whether a LC-DT combined approach is practical, feasible and beneficial in real-world conditions. For this purpose, as shown on Table 4 and Table 5, a matrix was developed to analyze the interaction between LC principles (Sacks et al., 2010) and DT functionalities or "technical functions" (Al-Sehrawy et al., 2021). In this analysis, a sample of six DT case-studies collected from the literature are considered as 'real world cases' to assess the alignment or degree of affinity of DTs with a set of LC principles. Thus, the interaction between DT functionalities and LC principles are identified and assessed following the methodology used by Sacks et al. (2010) in their study. Interactions are indicated by a symbol (+ or -), whether the interaction is positive or negative, and a (number) between brackets indicates the bibliographic reference. In the rows of Table 4 and Table 5, twenty four (24) LC principles are listed, as consolidated by Sacks et al. (2010) in their analysis of the interaction between Lean and BIM. In their columns, the DT cases-studies are described according to the "DT Use Case Classifications System (DTUCS)" proposed by Al-Sehrawy et al. (2021) in the context of urban planning and city infrastructure management. This system suggests a taxonomy to characterize and classify DT-applications. It includes four high-levels of *"Included Uses" (i.e., Mirror, Analyze, Communicate and Control)*

Table 4: Assessment of interactions between DT functionalities and LC principles (Part I).

LC principles		**DT technical functions**															
		Mirroring					**Analysis**				**Communicating**					**Control**	
Principal area Principle	**Id.**	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI
Flow process																	
Reduce product variability	A	+(5)						+(5)	+(5)		+(5)						
Reduce production variability	B		+(2) +(1)				+(2) +(6)	+(2) +(5)				+(2)					+(2)
Reduce production cycle duration	C	+(3)					+(2) +(3)	+(2)		+ (4)		+(2) +(4)					+(2)
Reduce inventory	D																
Reduce batch sizes	E																
Reduce changeover times	F																
Use multiskilled teams	G																
Use pull systems	H																
Level the production	I																
Standardize	J																
Institute continuous improvement	K						+(2)	+(2)			+(6)		+(5)				
Visualize production methods	L		+(2)					+(2)				+(2)					+(2)
Visualize production process	M	+(3)	+(1)		+(4)		+(3) +(1)				+(6) +(1)	+(4)					
Simplify	N	+(3) +(6)			+(4)		+(6)			+ (4)			+(5)				
Use parallel processing	O																
Use only reliable technology	P	-(1) -(3)	-(1) -(6)		+(4)		+(2) -(3) -(6)	+(2) +(5)	+(5)	+ (4)			+ (4)	+ (5)			-(2)
Ensure the capability of the production system	Q																

and a set of *"Specialized Uses"*. The *"Specialized Uses"* for each of the DT *"Included Uses"* were denoted by roman numbers as follows: *Mirror (I: qualify, II: quantify, III: monitor, IV: capture) Analyze (V: qualitize, VI: predict, VII: simulate, VIII: mine, IX: compute) Communicate (X: engage, XI: transform, XII: document, XIII: immerse, XIV: visualize)* and *Control (XV: actuate, XVI: inform).*

Table 5: Assessment of interactions between DT functionalities and LC principles (Part II).

LC principles		**DT technical functions**															
				Mirroring				**Analysis**				**Communicating**				**Control**	
Principal area Principle	**Id.**	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI
Value generation process																	
Ensure requirement capture	R																
Focus on concept selection	S																
Ensure requirement flow down	T																
Verify and validate	U								+(5)								
Problem solving																	
Go and see for yourself	V	+(3)				+(4)					+(3)	+(4)					
Considering all options	W																
Developing Partners																	
Cultivate network of partners	X								+(5)								

In addition, Table 6 describes this interactions and the authors' explanations and arguments while classifying the DT cases (from the literature) in Table 4 and Table 5; however, due to page limitations, only two of the six case-studies considered in this analysis are presented.

Table 6: Example of processes to assess the interaction between DT and LC for SQR3.

Item / Reference Use case Description / Involved DTT (DAT, DPT, IMT)	**Description of DT-LC interaction and Impacted LC principle**
+(2) / (Jiang et al., 2022) / In this study a DT was developed to simulate the assembly process of modular construction. This application collected and integrated real-time information from the process. / DAT: SM+UWB+RFID, DPT: Smart mobile gateway, IMT: Unity platform.	Thanks to the simulation and visualization capabilities of this application, it reduced production variability (B) by quickly detecting deviations, and reduced production cycle times durations (C) by obtaining real-time information. In addition, this DT improved the visualization of production methods (L) by centralizing information and facilitated the continuous improvement of the process (K) by analyzing the simulations.
(+4) / (Peng et al., 2020) / This study documents a DT application to integrate comprehensive information about the lifecycle of a building through the continuous capture, processing and visualization of *"static and dynamic data"*. This study highlights the integration and centralization of the building asset information into a unified control center (dashboard) / DAT: XR, DPT: AI+ Big Data, IMT: BIM	By processing capturing and processing in near-real data from multiple sources, this application could support various management processes. This application contributed to reducing cycle duration (C) by simplifying inspection activities and improving the visualization of the production process (M).

The DT applications considered in the analysis of Table 4, Table 5 and Table 6 were: (1) (Guven & Ergen, 2021), (2) (Jiang et al., 2022), (3) (Xue et al., 2022), (4) (Peng et al., 2020), (5) (Lee & Lee, 2021) and (6) (Shariatfar et al., 2022).

DISCUSSION

This study investigated the benefits and feasibility of the synergy between DT and LC in construction. The GRQ was answered positively. Then, the mutual benefits of the DT-LC integration were explored in SRQ1 and SRQ2, while its feasibility was assessed in SRQ3.

In terms of the benefits that DT can bring to LC (SRQ1), the findings show that DT applications—when used as a technological support—can help to overcome many of the barriers that limit the adoption of LC. On the technical and technological front, DT can improve information management, facilitate the collection of key LC-related metrics and indicators, enable the simultaneous use of multiple LC tools, and enhance the integration, accessibility, and visualization of LC-related information. However, DT integration may have limited impact on increasing general awareness or understanding of LC thinking. In terms of cultural and organizational barriers, DT can improve communication and collaboration among stakeholders, including customers and supply chain, which in turn can help reduce resistance and risk aversion to investing in LC initiatives. These improvements suggest that DT can increase the value that LC brings to the AEC industry by making its implementation more practical and its beneficial impact stronger and more measurable.

In terms of the value that LC can add to DT in construction (SRQ2), the results suggest that LC— when used as a guiding theory for process improvement—can increase the relevance and acceptance of DT in construction. This helps to move the adoption of DT beyond a purely technological trend to ground it in process-driven objectives. For example, LC tools such as LPS and JIT can support supply chain integration, thereby increasing the usefulness and scope of DT in construction. However, it is important to note that LC integration does not address certain technical challenges, such as interoperability. To overcome this challenge, DT development can leverage potential interoperability enablers like Industry Foundation Classes (IFC), Sensor Model Language (SensorML), and semantic technologies.

To address the feasibility of DT-LC integration, the degree of affinity between LC principles and DT functionalities (SRQ3) was assessed using a matrix of interactions. The results reveal that all the DT case studies analyzed show alignment with one or more LC principles, particularly those related to "improving the flow" of the construction process. Most of DT analyzed showed potential for reducing variability, shortening production cycles, improving production visibility and supporting continuous improvement. However, a recurring negative assessment was observed in relation to the principle of "using reliable technology". This because most of the DT applications studied were developed using experimental technologies or in pilot environments, making them unsuitable for immediate large-scale deployment. Although some of them incorporate well-established tools such as BIM, GIS, or RFID, the overall DT solutions were still not considered fully reliable for full-scale implementation.

Comparing these findings with related studies in literature, we found that, while there is increasing support for DT-LC integration, most existing studies tend to emphasize the benefits of DT-LC integration or advocate for its adoption, without systematically assessing key aspects of this integration. For example, Sepasgozar et al. (2021) proposed to enhance BIM capabilities for LC implementation through using IoT to automate data collection, but they did not assess in depth the practical advantages or disadvantages of this integration. Sacks et al. (2020) introduced the concept of Digital Twin Construction (DTC) to integrate digital technologies (e.g., BIM, IoT and AI) with LC to provide accurate status and proactive analytics for the construction process. Although they address informational, technical and conceptual aspects of this approach, they did not assess the specific impact of this integration on DT and LC individually. Altan and Işık (2023) conducted a study with a broader perspective by identifying and evaluating the benefits, opportunities, costs, and risks of DT-LC integration. However, their study did not provide a systematic analysis of the barriers that continue to hinder the full adoption of DT and LC in practice.

CONCLUSIONS

The purpose of this work was to enrich the discussion on the integration of DT and LC in construction projects by applying comparative and feasibility analysis to three proposed scenarios (each addressing one SRQ) for this interaction. The analysis of the results for the SRQ1 leads us to believe that the technical capabilities of the DT can address an important factor that limits the strengthening and implementation of the LC, which is the management of information. The analysis of the results for SRQ2 suggests that if LC acts as the theory that improves the management and collaboration, the DT concept can benefit from increasing its usefulness and the scope of its action, thus achieving higher levels of awareness of its use in a construction process. The findings for SQR3 show a high theoretical affinity or feasibility between technological applications based on the DT concept and LC. This affinity is stronger with respect to the improvement of the production flow in a construction process, which is considered a pillar of the LC theory. Thus, although DT was not originally designed to support a specific managerial approach, its capabilities show a significant alignment with LC thinking. However, also as a result of this study, it is necessary to highlight the low capacity of a technological application to increase general knowledge on managerial theories as LC and the need to include in the development of an integrated DT-LC solution, the interoperability issue as a key challenge to achieve effective integration. Seriously addressing interoperability and current solutions for it may be one of the keys to enable the evolution of DT from an experimental stage to a widely used stage in managerial or any other application field.

Since most of the analysis in this study is based on the author's reasoning, important cautions must be taken in when generalizing the results of this analysis. However, this study should encourage researchers, AEC industry members and any other stakeholder interested in improving construction productivity to analyze more in depth the studied scenarios or to explore other perspectives on this integration, including practical implementation ones.

Future research on DT-LC integration can focus on evaluating or developing real-world case studies where LC implementation is supported by I4.0 technologies or DTTs (e.g., DAT, DPT, IMT, interoperability solutions) around a DT application. This would not only contribute to the real-world assessment (quantitative and qualitative) of the impact of one approach on the barriers or challenges that limit the implementation of the other approach, but also to the identification of the potential challenges of the new approach that this integration creates.

ACKNOWLEDGMENTS

The authors are grateful to the Natural Sciences and Engineering Research Council of Canada for its financial support through its CRD program 543867-2019. Generative AI was used for language and grammar improvement; the text was carefully read afterward to assure that the meaning was not altered.

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