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DIGITAL TWINS AND LEAN CONSTRUCTION: CHALLENGES FOR FUTURE PRACTICAL APPLICATIONS

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ABSTRACT

The construction industry has experienced the opportunity to incorporate new technologies to solve problems in terms of information flow, collaboration, quality, costs, productivity, and predictability. Digital Twins (DT) can support solving some of these problems, mainly when associated with lean principles. However, there are still many gaps in the literature regarding the state of practice of DT for construction. This study investigates how current research on the integrated use of BIM-based DT and lean for construction projects has been positioned in front of practical challenges, aiming to identify research directions that support future applications in the construction phase. The research method adopted was a Systematic Literature Review (SLR). A total of 14 publications were identified and analyzed from the perspective of challenges for practical applications, considering seven aspects regarding DT application in other industries: cognitive and technical level of people, technology and infrastructure, support tools, standards, and specifications, cost control and management, cyber security and intellectual property rights, and insufficient development of DT. The results suggest that the challenges for DT implementation may become more complex due to the dynamic and unique nature of the construction site and that there is still a large field for further research on DT with lean. Finally, some future research directions are proposed.

KEYWORDS

Digital Twins, Lean Construction, Production Planning and Control, Integration, BIM.

INTRODUCTION

The construction industry has recently increased using technological innovations to solve existing problems. Industry 4.0 has been used over the past few years to describe the trend toward digitization, automation, and the increasing use of information and communications technology (ICT) in the manufacturing environment (Oesterreich & Teuteberg, 2016). Construction 4.0 (or digital transformation in construction) has gained

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strength in this context, inspired by the Industry 4.0 environment. Despite advances, the construction industry still faces several complex issues, including dealing with waste, inefficiencies in terms of processes, information flows and collaboration, fragmentation, conservativeness, difficulty in quality and cost control, low productivity, low predictability, and insufficient development to generate innovation technologies (Sawhney et al., 2020; Opoku et al., 2021). Digital Twins (DT) can be understood as "a model for data-driven management and control of physical systems" (Sacks et al., 2021) that have the potential to respond to such construction problems (Opoku et al., 2021).

DT are based on physical and digital world integration. Its main components (physical, virtual equivalents, and data connection) have been used in Industry 4.0 in engineering, manufacturing, operation, and maintenance (Tao et al., 2019). DT are a new phenomenon in construction, and there is still no consensus among researchers and practitioners about their role in supporting design and construction (Opoku et al., 2021; Sacks et al., 2020). Construction projects have specific aspects that must be considered. They are site-based, individual, dynamic, complex, and involve information exchange and communication between different stakeholders (Oesterreich & Teuteberg, 2016).

Construction workflows involve the interaction of a large number and diversity of physical resources (personnel, equipment, and materials), many of which are temporary. In addition, construction projects have demanded the availability of ever more detailed status information to find and remove constraints, prepare tasks, define teams, and execute services. Lean principles offer a solid base for dealing with these issues; however, its methods require a considerable flow of information and resources, which are difficult to hold without the support of information technology (Sacks et al., 2020).

Sacks et al. (2020) recently proposed the Digital Twins Construction (DTC), based on Building Information Modeling (BIM), lean construction thinking, Artificial Intelligence (AI), and wide-ranging digital site monitoring technologies to create a "data-centric mode of construction management". According to Sepasgozar et al. (2021), some of the key objectives of DT with lean integration could be reducing variability, enhancing productivity, minimizing waste, improving workflow, increasing transparency, and optimizing deliveries. DTC can provide accurate status information and optimize design and construction planning and control, making construction management increasingly proactive (Sacks et al., 2020). The synergy with lean thinking is a relevant point in DTC workflow, as is the use of BIM to contextualize related data.

Despite the benefits, according to Sacks et al. (2020), much research and development work will be needed to progress the DTC workflow and enable more future practical applications. Boje et al. (2020) and Opoku et al. (2021) also investigated the definitions, concepts, structures, limits, and requirements necessary for DT adoption in the construction industry. The authors are unanimous in suggesting that these discussions are just beginning, and there are gaps mainly regarding practical applications.

Tao et al. (2019) developed a study regarding DT application in the smart manufacturing field. They summarized the challenges for its practical application in seven aspects: (1) cognitive and technical level of people, (2) technology and infrastructure, (3) support tools, (4) standards and specifications, (5) cost control and management, (6) cyber security and intellectual property rights, and (7) insufficient development of DT. Those aspects seem general enough to resemble common challenges in the construction field. Therefore, this study investigates, from an exploratory approach, how current research on the integrated use of BIM-based DT and lean for construction projects has been positioned in front of practical challenges. The main expected contribution to the body of knowledge are some research directions supporting future applications in the construction phase.

Following this introduction, the next section presents background research, including DT definitions, technologies, and applications. Section "Research Method" outlines the methodology for selecting the articles reviewed. Section "Results" present the results of the review. Section "Discussion and Future Directions" presents some findings after the content analyses. Finally, the final considerations are summarized in the "Conclusion."

DT DEFINITION, TECHNOLOGIES, AND APPLICATIONS

The concept of DT emerged in 2003 (Grieves, 2014), but it is only now achieving more value in the industry. Currently, the first difficulty faced for the broad adoption of DT is the absence of a mutual and clear conceptual definition. As a result, researchers from different universities and institutes proposed their understanding according to their specific fields of application in the industry (Opoku et al., 2021; Tao et al., 2019).

For example, in the smart manufacturing context, DT has been understood as an emerging and pragmatic paradigm built on the concept of Cyber-Physical Systems (CPS), which aims an architecture to converge the physical and virtual spaces (Tao et al., 2019). Opoku et al. (2021) report that in more digitally advanced sectors, such as manufacturing, automotive, and aerospace, DT has been used in predictive maintenance, structural health management, shopfloor management, product life cycle management, and machinery fault diagnosis, for example. DT can be expected to experience rapid development over the next few years (Tao et al., 2019). Tao et al. (2019) summarize the value of DT for smart manufacturing in the following aspects: increasing visibility, reducing time to market, keeping optimal operation, reducing energy consumption, reducing maintenance cost, increasing user engagement, and fusing information technologies.

In the scope of this article, and considering the application to the construction stage, DT can be understood as up-to-date digital representations of a given system's physical and functional properties (Sacks et al., 2020). This system can be a physical artifact, a social construct, a biological system, or a composite system, such as a construction project, that have characteristics of physical products and social systems (Sacks et al., 2020).

DT is built on integrating various technologies and concepts of Industry 4.0. Possible integration interfaces involve data acquisition, storage and analysis, what-if scenario simulations, and visualization. Examples of related technologies and concepts are Modeling and Simulation Tools, Internet of Things (loT), Cloud Computing, Machine Learning (Tao et al., 2019), Global Positioning System (GPS), Tag Identification Systems (such as RFID or QRCode), Scanners, Camera, Big Data, Blockchain, (Opoku et al., 2021), Digital Ecosystems, Unmanned Aerial Vehicles (UAV), Virtual Reality (VR), and Augmented Reality (AR) (Sawhney et al., 2020).

In the built environment, BIM has the potential to compose the virtual counterpart of DT (Pishdad-Bozorgi et al., 2020; Sacks et al., 2020), providing significantly improved spatial context for acquired data (Gao et al., 2018) and broader situational awareness for managers (Sacks et al., 2020). However, Sacks et al. (2021) emphasize that DT is not simply an evolution from BIM or an extension of BIM tools integrated with technological solutions to sense and monitor the physical environment. A DT for construction is not limited to digitally recreating the physical system but is also connected to it automatically.

The DTC proposed by Sacks et al. (2021) is not limited to BIM capabilities. Still, it is a construction mode based on PDCA (Plan, Do, Check and Act) and lean principles, which provide reliable and timely information for management decision-making. In addition, the PDCA approach provides a cyclical and closed control mechanism that reflects the comprehension of the temporary nature of construction projects, which can and should benefit from lean practices (Sacks et al., 2020).

AI is also a central component, which can be understood as an umbrella term for applications in which machines develop human-like intelligence, dealing with learning, judgment, and problem solving (Weber-Lewerenz, 2021). Another relevant component is the data flow connection in a DT (exchange of data, information, and knowledge), which is mainly made possible by the development of IoT (Boje et al., 2020; Sacks et al., 2020). IoT infrastructure includes communication networks and protocols, software, hardware, and cloud computing platforms (Al-Fuqaha et al., 2015).

In construction sites, the possible applications of DT involve site monitoring and optimization, equipment management, asset management, supply chain management, worker-power management, and safety analysis, among others (Zhang et al., 2021). In the PDCA approach, DT can work in the following domains: (a) Plan: construction plans, (b) Do: fabrication and construction, off and onsite, (c) Check: monitoring (comparing as-built product and as-performed), and (d) Act: improve design, construction, and operation with changes to plans based on feedback received (Sacks et al., 2020).

RESEARCH METHOD

According to Kitchenham (2004), the Systematic Literature Review (SLR) approach identifies, evaluates, and interprets the relevant literature related to a specific research question, a specific field, or a phenomenon of interest. The SLR was implemented to map previous literature and meet the study's objectives. The research gap was converted into the following research question: “How has been the literature on BIM-based DT for construction and lean positioned regarding the challenges for its practical application in real contexts, mainly in the construction phase?”. Fig. 1. illustrates this research process.

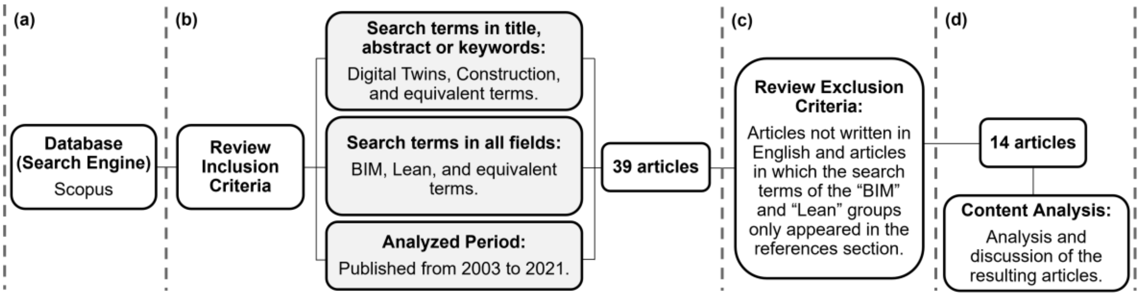

Figure 1: SLR research process.

Search strategy: the research process included the following macro steps: (a) Definition of a database; (b) Definition of review inclusion criteria and search parameters; (c) Definition of the review exclusion criteria; and (d) Content analysis. Scopus was the selected search engine due to its broad coverage of relevant academic articles.

Inclusion criteria: initially, the research groups were defined. After some scoping studies, related terms and terms considered equivalent were included in each group. Each article (Article, Conference Paper, or Review) should contain at least one search term from each group. For the "Digital Twins" and "Construction" groups, the search terms were specifically searched for in the title, abstract, or keywords of the articles in the databases. For the “BIM” and "Lean” groups, the search included all fields in the documents. The data range included articles published from 2003 (when the concept of

DT emerged) to 2021. A total of 39 articles were obtained with the inclusion criteria. The search terms used to establish the conceptual boundaries of the review are as follows:

1. Digital Twins: "digital twin"; "digital twins"; "virtual counterpart"; "digital replica"; "virtual twin".
2. Construction: "construction industry"; "construction sector"; "construction engineering"; "construction management"; "construction engineering and management"; "civil engineering"; "construction project"; "construction projects"; "construction site"; "AEC"; "AECO"; "construction 4.0".
3. BIM: "building information modeling"; "BIM"; "building information model".
4. Lean: "lean".

Exclusion criteria: the first criterion was the removal of articles not written in the English language, chosen due to its recognized universality. The second criterion was the manual removal of the articles in which the search terms of the "BIM" and "Lean" groups only appeared in the references section. This step resulted in 14 articles as the final sample.

Content analysis: the final sample was analyzed and discussed according to seven challenges for DTs practical applications defined by Tao et al. (2019) (Table 1).

Table 1: Challenges for DTs practical applications (Tao et al., 2019).

Challenges	General Description
1-Cognitive and technical level of people	It refers to the comprehensive understanding of DT and its values, the psychological and cultural boundaries that can hinder the adoption, and the technical capacity to operate DT.
2-Technology and infrastructure	It refers to technological development, the availability of related commercial products, and infrastructure aspects.
3-Support tools	It refers to clarity about available commercial support tools (software and hardware) and its current integration capacity.
4-Standards and specifications	It refers to standards specifications to ensure data exchange, integration, and fusion across models, interfaces, and protocols.
5-Cost control and management	It refers to the balance between DT costs and benefits, considering the need for time-consuming and labor-intensive, and the need for high-performance hardware and software support.
6-Cyber security and intellectual property rights	It refers to protecting confidential information to ensure security (protecting networked systems and resisting malicious attacks on sensory devices) and protecting intellectual property rights.
7-Insufficient development of DT	It refers to the clarity of concepts, availability of tools, technologies, and skilled people, and market, business, and investment strategies.

RESULTS

The sample includes 6 Articles (46,2%%), 6 Reviews (46,2%), and 2 Conference Paper (7,7%). The number of documents published per year was two documents in 2019, two in 2020, and ten in 2021. This section presents the content analysis, considering the challenges proposed by Tao et al. (2019).

1-COGNITIVE AND TECHNICAL LEVEL OF PEOPLE

Technologies are developed, designed, and used by humans, so a sustainable and ethical digital transformation in construction can only be successful if people are at the center of discussions (Weber-Lewerenz, 2021). Lean systems also adopt this point of view

(Sepasgozar et al., 2021). Weber-Lewerenz (2021) studied digital innovation in construction from a multidisciplinary perspective of Corporate Digital Responsibility (CDR). This approach can serve as a guideline for the DT operational development with ethics, morals, and sustainability. The authors pointed out that companies currently lack knowledge about the possible DT applications regarding construction workflows. Weber-Lewerenz (2021) identified an urgent need for skilled staff to implement new digital technologies in companies, representing a practical gap. There is also a need for educational strategies to help the practitioners with the multidisciplinary skills needed to deal with digitalization and its social and ethical aspects. However, digital technologies themselves can be helpful in the augment newly required skills. For example, Sepasgozar (2021) mentioned the use of VR for educational training. DT development will require multidisciplinary skills in sensing technologies, construction management, organizational sciences, data science, applied mathematics, theoretical and computational statistics, and computing science (Sacks et al., 2020). Besides that, another pointed issue is a possible cultural resistance from the skilled construction workforce to the required changes in management systems and practices (Sacks et al. 2020, Sepasgozar et al., 2021; Marocco & Garofolo, 2021). The organizational fragmentation in the construction industry can hinder the extensive process change required (Sacks et al., 2020). A first step to overcoming this boundary can be an awareness strategy for elucidating individuals concerning DT value for construction (Sepasgozar et al., 2021).

2-TECHNOLOGY AND INFRASTRUCTURE

Sacks et al. (2020) suggested the following areas for future technological DT development: data fusion to deal with the multiple data streams and derive status information; mechanisms for data storage, protocols, and algorithms for data consistency; data science methods and algorithms for monitoring, processing, interpretation, simulation, and optimization; and applicability of AI tools. According to Sepasgozar et al. (2021), concerning the connection, IoT technologies can act as integrators of lean-BIM systems, supporting DT development. Moreover, the future availability of 5G will facilitate the transfer of large data streams (big data) for real-time controls and immediate scenario optimizations. On the other hand, Sacks et al. (2020) pointed out that BIM has satisfactory tools for product design representation but lacks essential elements regarding DT for construction, such as full semantics. For example, their geometry models use object-oriented vector graphics, which is not ideal for dealing with point clouds.

Furthermore, the BIM object models do not accurately represent aspects of the construction process (Sacks et al., 2020). Another challenge worthy of investigation refers to decision-making processes. There is a need for studies focusing on machine learning algorithms to create accurate prediction models for construction (Marocco & Garofolo, 2021; Sacks et al., 2020). Regarding lean, Sepasgozar et al. (2020) indicate a gap in understanding the synergistic interactions of lean concepts and the combination of digital information and sensor-based technologies in construction applications. According to these authors, there are many advanced technologies commercially available, and there is a high demand to use them for lean purposes. However, the number of validated case studies using advanced technologies is still limited.

3-SUPPORT TOOLS

According to Sepasgozar et al. (2021), the literature suggests some types of tools already available for DT in other industries, especially in three layers: communication, protocols applications, and platforms for data analytics. According to Sacks et al. (2020), preview studies evaluated many digital site monitoring technologies, and some have become available commercially. Lee et al. (2021), Jiang et al. (2021), and O'Grady et al. (2021) tested some commercial tools used for DT development in their specific use cases. Lee et al. (2021) suggested a framework for integrating DT and blockchain for construction. They used IoT sensors to collect data from the construction and Azure (Microsoft) as the cloud service platform, providing the blockchain service modules. For building DT, the authors used Unity, a game engine that supports plug-ins for BIM data transfer, sensor synchronization, and real-time visualization (Lee et al., 2021). Jiang et al. (2021) described the MiC blockchain's steps. They mentioned Revit, Maya, or Solidworks as commercial solutions to create the 3D models imported into Unity to build DT functions. DT was converted into JavaScript language through Web Graphics Library (WebGL). O'Grady et al. (2021) proposed a new approach with VR, BIM, and DT to advanced learnings and experiences of the circular economy in construction. They prepared the BIM model in Revit and then exported it for Unity. DT can benefit from solutions provided as services, such as web-service platforms (Marocco & Garofolo, 2021; Boje et al., 2020). According to Sacks et al. (2021), DT for construction are based on systems that incorporate hardware, cloud, and advanced information processing resources, which remain invariant independent of construction project type variations. As such, DT for construction could be delivered as a platform business model, in which an external company provides the infrastructure and integrated hardware/software service. Although several support tools have been identified, the literature review indicates that, despite efforts in this direction, there is still a gap regarding robust and integrated commercial DT solutions for construction that could be implemented on construction sites.

4-STANDARDS AND SPECIFICATIONS

DT can involve various data collection devices storing information in diverse formats, which leads to fragmentation, data heterogeneity, and a lack of interoperability. These issues can decrease the construction industry's readiness for DT adoption (Marocco & Garofolo, 2021; Sepasgozar, 2020). According to Sacks et al. (2020), data standardization in consistent syntactic and semantic formats is essential for the DT workflow in construction projects, so protocols and algorithms development for this purpose are critical topics for future research. According to Boje et al. (2020), the interoperability problems have already been the topic of studies on BIM and multi-dimensional (nD) modeling, which refers to BIM domains, uses, or use cases in different contexts. For example, 4D modeling is related to the "time" dimension, so all the analysis of the represented processes occurs from a temporal perspective. The complex nature of nD models, general problems of cohesion, and poor synchrony have left BIM lacking in interoperability and automation. This lack can hinder the required real-time connection in DT. Schemes such as the IFC have improved the exchange of information and collaboration in BIM applications. Still, the authors point out that an eventual transition from the IFC format to a more open and web-linked data paradigm would ensure that the correct data will be available at the right time. According to the authors, solutions to link data in BIM have been proposed in the literature. For example, semantic web-compatible formats, such as OWL and RDF. Therefore, developing a common semantic web platform for DT with IoT and AI could be a big step towards interoperability and expansion into future lifecycle stages. Following another approach, Jiang et al. (2021) mentioned that blockchain could provide unified standards and protocols to support transparent and secure information sharing in DT.

5-Cost control and management

Many authors have discussed the cost savings generated by DT adoption in the project life cycle management (Marocco & Garofolo, 2021; Weber-Lewerenz, 2021; Lee et al., 2021; Sepasgozar, 2021; Jiang et al., 2021; Schimanski et al., 2020; Boje et al. 2020). Smart and lean construction supported by DT can further reduce waste and energy consumption, for example. However, despite the relevance of this aspect, only Opoku et al. (2021) briefly considered the cost implications of implementing the DT. According to the authors, an adequate cost estimate for the application of DT depends on the scope and objectives involved so it can vary depending on the level of sophistication required. Generally, despite involving high initial investments, DT tends to present a cost reduction throughout the project life cycle, in addition to the compensation generated by the savings resulting from its application. No further details are provided.

6-Cyber security and intellectual property rights

Some aspects that require attention in the design of DTs are data security, data protection, data ownership, level of accessibility by each stakeholder, privacy, and prevention of cyberattacks (Weber-Lewerenz, 2021; Marocco & Garofolo, 2021; Boje et al., 2020; Sacks et al., 2020; Mêda et al. 2021; Sepasgozar, 2021). The responsible sharing of information among the stakeholders involved in DT applications requires that all data transactions be tamper-proof, transparent, traceable, and reliable, minimizing any possibility of manipulation (Lee et al., 2021). Blockchain integration with DT can provide needed decentralization and security to ensure immutable data exchange among various stakeholders (Sepasgozar, 2021; Marocco & Garofolo, 2021; Lee et al., 2021; Jiang et al., 2021). Lee et al. (2021) proposed a DT integrated into a blockchain framework to support responsible information sharing in construction projects. A possible application is in the execution of smart contracts, a self-executing contract protocol capable of automatically facilitating, verifying, or enforcing established terms, including purchase and payment agreements. For example, a smart contract can automatically signal the supply chain to stop production/shipment of offsite products if there is any delay in the onsite assembly schedule. This action can save logistics costs, ensuring that only the right material is in the right place and at the right time, following lean principles. Jiang et al. (2021) proposed a blockchain-enabled cyber-physical smart Modular Integrated Construction (MiC) platform. The authors also pointed out that blockchain facilitates security and privacy for exchanging data and sharing services in DT workflows.

7-Insufficient development of DT

DT adoption will require many multidisciplinary skills. In addition, new business models will be critical to ensure the delivery of technical aspects of DT. The analyses by Sacks et al. (2020) indicated that the Construction Tech startup companies would probably be better positioned to promote the expected transition to DT than traditional construction companies. Although many startup companies that monitor construction sites have emerged in recent years, the efforts still have been isolated, not achieving a coherent DT whole. Currently, there is a lack of a common framework for creating DT models on a large-scale (Sepasgozer, 2020, Boje et al., 2020). Concerning lean construction, Sepasgozar's et al. (2020) findings suggest "a large clear gap in understanding synergetic interactions of the lean concepts and the combination of digital information and sensor-based technologies in specific fields of construction". This topic should motivate future research. Currently, researchers have been investigating requirements for value creation, provision of insight, security, quality, federation, and curation to support DT adoption (Sacks et al. 2020). Weber-Lewerenz (2021) also suggests a strong need for future guidelines, standards, and binding rules, also in legislation, to support the construction digitalization process (including DT adoption) with moral and ethical principles.

DISCUSSION AND FUTURE DIRECTIONS

The discussion in the literature about the cognitive and technical levels required of people is still developing. There will be a need to clarify individuals concerning the value delivered by the DT, considering that it is an emerging concept. An awareness strategy can help as a first step to reducing problems with possible cultural or psychological boundaries. Besides that, while there is a need for educational approaches to help with the required new multidisciplinary skills, the construction industry still faces old challenges related to workforce skills. There are still existing problems with waste, low productivity, and organizational fragmentation that require a change in the workflow basis. Therefore, complete DT integration with the lean construction principles will be essential to achieving an effective digital transformation in construction.

Many authors have discussed the technology and infrastructure aspect and pointed out future directions for research and development in areas such as data science, IoT, and BIM semantics. However, the review suggests that related technologies have not been tested enough in the complex environment of the construction site, which involves the dynamic interaction of diverse physical resources on many work fronts. In environments such as smart manufacturing, the main product generally moves along production lines at the pace of machines. In construction, the main product remains fixed while physical resources move around. This aspect becomes a challenge in DT modeling compared to other industries. To ensure DT's usefulness, the simulations must consider many variables linked to the behavior of many people working on construction sites and the flow of many materials and equipment, which can involve a high level of complexity. Besides that, currently available DT support tools are poorly integrated. For example, there are technologies, such as laser scanners, to derivate BIM models from point clouds, but few solutions make this model fully operational. There are also solutions for displaying sensor data in the BIM model. Still, the possible analysis does not leverage all the model potential – the model only organizes which entities pertain to a specific dataset.

On the other hand, there are efforts in the literature to deal with standards, complex challenges, and specifications, which will probably be reflected in practical application problems. Insufficient information about the related cost is another practical problem that can hinder DT adoption in construction. Users need to consider the balance between costs and benefits brought by DT before adopting it. The costs involve at least hardware/software/services to monitor and manage the entire construction site, including many work fronts. Considering the complexity, the cost to implement DT on the construction site will probably be higher than the cost to implement DT on the shop floor, for example. DT can benefit from the existing blockchain and BIM frameworks concerning cyber security. The results suggest that there is still a large field for further research on DT with lean integration. To Sacks et al. (2020), implementing the DT will require overcoming technical, sociological, organizational, and commercial barriers. The present study explored some aspects related to the challenges for practical application in the construction site that should be considered for future implementations of the DT for construction. Some future research directions for DT with Lean Construction are suggested in Table 2.

Table 2: Research directions based on the seven challenges.

Challenges	Research directions
1	What skills and training types will be required to adopt DT? How can DT with Lean contribute to improving workflow and reducing waste, considering different levels of knowledge of workers and different work fronts? Investigating the experience with other Industry 4.0 technologies can provide some insights.
2	How can the existing practice of BIM nD support simulations in DT for construction sites? How can Lean (and approaches such as location-based management systems) organize and make the results more predictable? How to implement the continuous information loop from the construction site and management actions to ensure that the work execution follows the pace planned? How predict or manage the behavior of a work team? How to include and model the supply chains?
3	What are the main commercial tools available for DT layers and their current maturity level? Considering lean principles, what are the requirements for enabling its integration into business model platforms?
4	What standards and specifications are required to integrate models, interfaces, protocols, and data involved in DT for construction?
5	What services and elements should be represented in DT? Does it make sense, for example, to consider only the services that are on the critical path, aiming to reduce the costs of construction site monitoring? What is the required maturity level for the DT development to balance the processing cost and the added value to the construction project?
6	How can workflows adopted in the BIM context contribute to cyber security and intellectual property rights in DT implementation?
7	There are still many gaps for future research, such as clarifying concepts; developing guidelines, standards, and binding rules; creating new business models, and increasing the synergy with lean principles.

CONCLUSIONS

This paper contributes to the body of knowledge by reviewing the current research on the integrated use of DT and lean for construction projects, considering existing practical challenges. A total of 14 articles were identified and reviewed. The content analysis of the existing literature suggests that although DT is a recent research trend, there is still a large field for further research, mainly on practical integration with required technologies and lean principles. The results indicate that while the construction industry is probable to face the same general challenges as other industries in implementing DT, such challenges may become more complex due to the dynamic and unique nature of the construction site. This article contributes to some future research directions based on the seven related challenges. It is expected that they can guide other studies on the subject. It is recommended that the academic community and practitioners consider these challenges to support a deeper investigation of the synergy between lean construction principles and DT in future work.

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