

ALIGNING DIGITAL SAFETY TECHNOLOGIES WITH LEAN CONSTRUCTION PRINCIPLES

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ABSTRACT

Digital safety technologies have been increasingly promoted as tools for enhancing construction site operations. While the value of technological innovation has been well established in management functions such as planning, monitoring, and control, its theoretical integration into construction safety management and its contribution to lean construction principles remains underexplored. Existing studies tend to focus on individual technologies or operational outcomes, offering limited insight into how digital safety activities systematically support lean objectives. To address this gap, this study conducts a literature review to develop an interaction matrix that conceptually aligns digital safety activities, defined in a Taiwanese technical guideline, with lean principles. A total of 44 cross-interactions is identified and substantiated by evidence from the literature. The results indicate that achieving lean principles requires a comprehensive digital safety management system, with particular emphasis on the digitalization of site hazard identification. Digital hazard identification is shown to reduce human effort and error-proneness while supporting multiple lean objectives simultaneously. By mapping these interactions, this study provides a foundation for prioritizing digital safety activities and offers directions for future research on the integration of digital technologies and lean construction safety management.

KEYWORDS

Lean construction, lean principles, digital technologies, safety.

INTRODUCTION

Lean construction has been widely recognized for improving project delivery efficiency while also contributing to accident reduction on construction sites. From a lean perspective, accidents and injuries are considered a form of waste because they negatively affect key project resources, including cost, time, productivity, and jobsite social culture (Gambatese et al., 2017). Consequently, safety management has increasingly been viewed as an integral component of lean construction rather than a parallel function. Previous studies have explored how lean thinking can enhance construction safety management, including lean-based safety planning, performance measurement, risk forecasting, and preventive strategies (Ghosh & Young-Corbett, 2009). Specific lean tools, such as the Last Planner System, 5S housekeeping, and error-proofing, have been shown to reduce accidents and improve safety performance (Bashir et al., 2011; Bajjou et al., 2017). Empirical evidence has further confirmed positive associations between lean adoption and safety outcomes (Demirkesen, 2020; Aisheh et al., 2022).

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Collectively, these studies establish lean construction as a credible theoretical foundation for improving safety management.

The application of digital technologies in construction has grown substantially over the past decade. However, existing research on digital technologies within lean construction has predominantly focused on planning, monitoring, and controlling functions, with limited attention given to safety management. Digital technologies such as BIM, IoT, and other production management systems have been studied and linked to process improvement through lean practices, particularly in terms of workflow reliability, productivity, and decision-making efficiency. Recent studies have begun to examine integration of lean construction with digitalization. Albalkhy et al. (2024) explores the interaction of IoT application with lean principles for waste elimination and value generation in construction. Liu et al. (2024) creates a framework of management methods for digital lean construction. While these studies show how digital tools can operationalize lean principles in production management context, safety-related applications are often treated as secondary. As a result, despite the existing associations between lean principles and safety objectives, the role of digital technologies in supporting safety management within a lean framework remains insufficiently examined.

At the same time, although numerous digital safety technologies have been proposed, it remains unclear which digital safety functions should be prioritized to effectively support lean construction. The existing digital site safety approaches have leveraged technologies such as computer vision, deep learning, and IoT to enable proactive hazard identification and real-time risk control (Xu et al., 2022; Jiang et al., 2021). They have been studied more broadly, outside the lean context, as means to improve overall project and safety performance. However, reviews on these safety technologies mainly focus on capabilities, adoption, and barriers. The literature lacks a systematic and theory-driven explanation of how specific digital safety functions can be understood and integrated into overall management system. This creates difficulty for both researchers and practitioners regarding technology selection and implementation priorities.

To address these two gaps, this study aims to systematically examine how digital safety functions support lean construction principles. Given that prior studies suggest lean can support safety objectives, aligning safety digitalization with lean principles may offer a useful basis for strengthening safety management and overall project performance by adding value, reducing waste, variability, and cycle time. Specifically, this paper develops an interaction matrix, based on a comprehensive literature review, to map digital safety activities to lean principles and articulate the underlying mechanisms of interaction. The digital safety activities are classified according to a technical guideline (white paper) in the Taiwanese context (Lin et al., 2025). By identifying and theorizing these interactions, the study provides a foundation for hypothesis development and future empirical testing. In addition, the proposed framework offers practical guidance for prioritizing digital safety technologies through the lens of lean construction objectives.

RELATED WORKS

Several studies have aligned lean theory with other paradigms in order to examine potential synergies. Sacks et al. (2010) investigated the interaction between lean and Building Information Modelling (BIM), which reveals the significant synergies amongst the two. Albalkhy et al. (2024) explores the integration of lean and Internet-of-Things (IoT) in construction, finding that they align mostly in the “flow” principles of lean. In the safety perspective, Antillón et al. (2011) similarly explored how lean practices affect project safety performance through an interaction matrix, also resulting in a significant amount of synergy. Saurin et al. (2006) have explored how safety is managed in a lean perspective through automation and visual management, while also proposing guidelines for lean safety approach. Another perspective of safety performance was explored by Gambatese et al. (2017), who aligns

worker safety behaviour with lean principles and practices. The alignment results provided insights on how to improve worker safety in construction. However, these body of literature haven't touched the new trending paradigm of digital construction site.

The lean theory and digital construction linkage research has just begun to emerge. Guerriero et al. (2017) describes how BIM and digital technologies support lean construction. Zavaleta and Pablo (2025) explored the framework of "Lean Construction 5.0", which brings new perspectives into what the traditional lean principles can bring into digital technology implementation. Furthermore, Dave et al. (2016) aimed at how IoT standards can enhance lean construction management. Linking and aligning lean principles with digital construction philosophies is an area that existing research has yet to address comprehensively.

Particularly, since the adoption of digital safety technologies are increasing, there is a need for theory-based account to properly support safety objectives when implemented. Hence, this study utilizes a digital construction safety management white paper to explore how digital construction site manages the safety performance through a proven and practiced theory, which is lean principles. In other words, the matrix assesses how the emerging technologies align with lean principles when implemented on construction site.

The remainder of the paper is organized as follows. First, it explains how the matrix is constructed and interpreted as well as listing the lean construction principles and digital construction safety functions used in this study. Second, it reveals and discusses the main patterns observed in the matrix. Lastly, it acknowledges some limitations, accompanied with the conclusion

METHODOLOGY

This study adopts a qualitative, literature-based analytical approach to examine the relationship between lean construction principles and digital construction safety activities. The overall research process consists of four main steps: (1) defining the analytical dimensions, (2) constructing an interaction matrix, (3) identifying and supporting potential interactions through literature review, and (4) synthesizing the results for further analysis.

First, two analytical dimensions were defined to structure the investigation. Lean construction principles were adopted from Koskela (1992), providing a widely accepted theoretical foundation for lean thinking in construction. Digital construction safety functions were defined based on an established Taiwanese technical guideline (white paper), which categorizes key safety-related activities enabled by digital technologies. These two sets of principles and functions form the basis for the analytical framework and are described in detail in the following subsections of the methodology.

Second, a two-dimensional interaction matrix was constructed, with digital construction safety functions represented as rows and lean construction principles represented as columns. The purpose of the matrix is to systematically explore how the functional capabilities of digital safety approaches may support, enable, or potentially constrain the implementation of specific lean principles. Each cell in the matrix represents a potential interaction between a safety function and a lean principle.

Third, potential interactions were identified through a structured literature review. For each cell in the matrix, the study followed a two-step procedure: (1) examining whether a plausible interaction exists based on the definitions and intended purposes of the safety function and lean principle, and (2) searching the literature for empirical or conceptual evidence that supports the proposed interaction. The literature search was conducted primarily through Google Scholar using combinations of keywords associated with each lean principle and each digital safety domain. Relevant studies were reviewed to determine whether and how digital safety functions contribute to lean objectives. The number of supporting studies identified for each interaction was recorded in the corresponding matrix cell, allowing a transparent representation of the

extent of existing research support (darker colored cells represent having more supporting studies for the interaction, in other words ‘synergy’, lighter colored cells).

Finally, the identified interactions were synthesized to form a basis for further discussion and interpretation. Cells without supporting evidence indicate that no meaningful relationship could be established based on the reviewed literature, either because the digital safety function does not directly support the corresponding lean principle or because existing evidence is insufficient. It is acknowledged that the literature reviewed in this study may not be exhaustive, and therefore the proposed interactions should be interpreted as theoretically grounded propositions rather than empirically validated relationships. The primary purpose of the interaction matrix is to provide an analytical foundation for future research to further assess, measure, and validate the relationships between digital construction safety and lean principles. In addition, the matrix offers practical guidance for stakeholders seeking to align digital safety technology implementation with lean construction objectives.

LEAN CONSTRUCTION PRINCIPLES

Initially, to challenge the conventional view of construction production as a set of conversion activities only, Koskela (1992) proposed the adoption of the new production philosophy for construction, as demonstrated previously by the manufacturing industry known as lean thinking. It implies that its activities can be viewed as flow processes containing both conversion and non-conversion activities, and that eliminating the latter improves performance. While lean thinking has already developed in manufacturing industry and was widely articulated by Womack and Jones (1996), Koskela (1992) organized eleven heuristic lean principles specifically to guide the design, control, and improvement of construction processes, noting that despite construction activity peculiarities, general flow principles still apply. The principles aimed at waste reduction, variability and cycle time reduction, transparency, and continuous improvement (Koskela, 1992). Although Koskela (2000) later formalized TFV (transformation-flow-value) as a broader production theory, this study selects the earlier eleven principles because they provide a concise, operational and construction-oriented heuristic set for flow process design, control, and improvement. The principles align with the present study’s safety management functions that reduce incident-related disruptions for interaction mapping. However, due to the relatedness of the principles with the digital safety functions, this study utilizes ten of the eleven principles by Koskela (1992) listed below with their assigned codes (P1-P10). These codes are used to denote lean principles in the interaction matrix: (P1) Reduce share of non-value adding activities; (P2) Constant consideration of customer requirements; (P3) Reduce variability; (P4) Reduce cycle time; (P5) Simplify by minimizing the number of steps, parts, and linkages; (P6) Increase output flexibility; (P7) Increase process transparency; (P8) Focus the control on the complete process; (P9) Build continuous improvement into the process; (P10) Balance flow and conversion improvements.

DIGITAL CONSTRUCTION SAFETY FUNCTIONS

Knowing the potential of digital technologies for improving construction safety, a comprehensive and structured approach is required to manage these technologies for effective implementation. To address this need, the Digital Construction Site Safety Management white paper published by the Taiwan BIM Alliance (Lin et al., 2025) proposed a systematic classification of digital safety activities. Despite the existence of other international guidelines and frameworks about smart safety, they only briefly describe the functions of various technologies without systemizing and describing the relationship with safety functions for practical safety management purposes. The white paper defines six safety activity domains, further operationalized through 17 safety functions. These functions were developed through an extensive review of existing reports, guidelines, and academic literature, and were

subsequently validated through expert interviews involving representatives from industry, government, and academia. Collectively, the proposed safety functions represent common construction site hazards and are intended to support practitioners in strategic planning and implementation of digital construction site safety solutions. Furthermore, they are well-suited for lean synergy exploration within the scope of this study. Hence, these six safety activity domains are adopted as one dimension of the interaction matrix.

The first safety activity domain, site security (S1), focuses on protecting the construction site from unauthorized access through preventive and monitoring measures. This domain includes functions such as access control, worker identification checks, and intrusion detection, which aim to reduce safety risks associated with unauthorized entry and uncontrolled site access.

The second domain, site hazard identification (S2), addresses hazards arising from site conditions and construction operations. This category emphasizes the use of digital technologies to detect, sense, and assess risks at an early stage and to issue warnings that enable preventive actions. It includes functions such as monitoring fall prevention measures, inspecting power distribution panels to prevent electrocution, identifying hazardous and controlled areas, verifying warning signs and protective measures, and monitoring heavy machinery operations.

The third domain, worker compliance monitoring (W1), concentrates on monitoring workers' exposure to immediate safety risks and ensuring timely protective interventions. Functions within this category include detecting compliance with personal protective equipment (PPE) requirements, identifying workers entering restricted or dangerous zones, and preventing struck-by accidents through proximity detection and real-time alerts.

The fourth domain, worker health monitoring (W2), extends safety monitoring to workers' physiological and ergonomic conditions. This domain focuses on identifying health-related risks such as abnormal heart rate variations, excessive fatigue, and improper postures, with the objective of preventing occupational injuries and long-term health issues through early detection and intervention.

The fifth domain, environment monitoring (C1), focuses on monitoring construction site conditions that may trigger structural or environmental hazards. This includes monitoring the stability of temporary structures and supports, as well as environmental factors such as temperature, air quality, noise, and other conditions that affect site hygiene, worker comfort, and safe working environments.

The final domain, safety management system (M1), represents a system-level approach to integrating digital safety technologies into construction safety management. This domain encompasses the integration of sensing facilities, databases, and digital platforms, along with mechanisms for data querying, visualization, and warning issuance. The objective of this domain is to support coordinated safety management, enhance compliance with safety standards, and enable informed decision-making at the site management level.

RESULTS

Table 1 presents the matrix, identified through the review. By analysing the interaction matrix, it provides multiple points of view of how lean principles are embodied in digital safety functions. A total of 44 cross-interactions were identified and serve as insights for guiding strategic focus in implementing digital safety technologies.

As a result of the review, 14 identified papers were selected to support the interaction cells, which are discussed in the following sections. Considering the numerous early lean studies supporting the digital safety functions, the findings reveal that lean studies have always been related with digitalization, in other words, digitalization and its proper implementation has always embodied lean principles. Furthermore, it is found that Koskela's novel work alone can be used to support many of the digital safety functions. The articles consulted is enough to serve

the purpose of exploring the alignments and by articulating those alignments can help readers to realize the benefits of implementing lean in construction digitalization.

Table 1. Interaction matrix of digital safety functions and lean principles

Digital safety activity Lean principle	S1	S2	W1	W2	C1	M1
P1 Reduce share of non-value adding activities	1	3	1	1	1	1
P2 Constant consideration of customer requirements	-	-	-	-	-	1
P3 Reduce variability	1	3	1	2	3	2
P4 Reduce cycle time	1	-	1	2	1	2
P5 Simplify by minimizing the number of steps, parts, and linkages	1	1	1	1	1	1
P6 Increase output flexibility	-	-	-	1	2	2
P7 Increase process transparency	3	2	3	-	3	3
P8 Focus the control on the complete process	1	1	-	-	3	1
P9 Build continuous improvement into the process	-	1	2	1	1	2
P10 Balance flow and conversion improvements	-	1	-	-	2	1

MOST LITERATURE SUPPORT FOR LEAN PRINCIPLES IN DIGITAL SAFETY

It can be observed that the interactions most strongly supported by the body of literature are S2 with P1 and P3, and C1 with P3, P7, and P8. S2 focuses on site hazard identification. It involves automated error-proofing mechanisms (Shingo, 1986) to prevent fall accidents from unsealed openings, and electrocution from abnormal power panels. By preventing accident-related events, it eliminates the possibility of non-value-adding activities (Koskela, 2000). In addition, it also inspects the appropriateness and visibility of warning signages and hazardous areas, which reduces uncertainty and variability (Schonberger, 1986). On the other hand, C1 focuses on site-related environmental conditions. By making structural health and environmental attributes visible with measurements, it enables management personnel to recognize deviations and stop the work when conditions aren't safe (Stalk and Hout, 1990). Consequently, it increases cycle time but in exchange for reduced variability and non-value outcomes (Shingo, 1986). Additionally, S1, W1, and M1 are aligned most with increasing process transparency (P7) because their systems display information and attributes through devices for activity adjustments and improvements.

DISTRIBUTION OF LEAN PRINCIPLES ACROSS DIGITAL SAFETY FUNCTIONS

The lean principles most strongly related to the digital safety functions are P1 (Reduce share of non-value adding activities), P3 (Reduce variability), P4 (Reduce cycle time), P5 (Simplify by

minimizing the number of steps, parts, and linkages), P7 (Increase process transparency), and P9 (Build continuous improvement into the process). The matrix suggests that digital construction safety embodies lean principles by being a data-driven, real-time perception, and collaborative system that reduces non-value activities by automating processes efficiently (Xu et al., 2022; Zhou et al., 2018).

The abundant alignment in the first principle of lean verifies that these functions avoid the source of non-value-adding activities (P1) by acknowledging and eliminating them before happening (Koskela, 2000). Since the digital safety functions mostly focused on preventing the causes of accidents and safety-related stoppages, most of them use a fail-safe system as described by Shingo (1986) to prevent safety-related errors or injuries. For example, S2 prevents fall accidents (Fang et al., 2018) and W1 prevents struck-by accidents can be monitored through IoT or vision-based devices (Wu et al., 2013), C1 continuously monitors structural stability to prevent failures (Kerrouche et al., 2009). Even if the system fails to prevent, it would have real-time response for the relevant management personnel to reduce the non-value outcome. Hence, with the controlled safe environment, uncertainty and reliability of workflow is being maintained (Ballard, 2001; Thomas et al., 2002). Consequently, they also align well with reducing variability (P3) and cycle time (P4).

Introducing technologies simplifies (P5) exhaustive but crucial tasks such as manual inspection, monitoring, and hazard identification. These technologies reduce the length of safety inspection workflow, possibly reduce cost, and with the correct tools/approach can reduce the chance of errors (Bashir, 2013). For example, (1) real-time worker health monitoring with digital wearables (Ahn et al., 2019) reduces the need for routine manual check-ups (W2), and (2) continuous structural stability monitoring with measurement tags (Wu et al., 2013) minimizes reliance on scheduled onsite inspection by certified personnel (C1).

The principle of transparency (P7) aims to make the production process transparent and make deviations visible for control and improvement (Brady et al. 2018). The lack of process transparency increases the tendency of error and eliminates motivation for improvement (Koskela, 2000). The digital construction site transforms safety-related information into shared, real-time visual cues, such as alerts and information display which enhance situational awareness and prevent unwanted safety outcomes (Reinbold et al. 2020). The mechanism is also known as visual management, which can be an important concept incorporated in digitalization of construction. Documenting and verifying personnel/vehicle entry by biometric or vision-based systems (S1) implements visual management concept by creating a visual platform through appropriate devices and linked with managerial routines and systems (Pedó et al. 2023). Ensuring warning signs and protective measures for hazardous areas are properly installed (S2), and issuing visible alerts whenever deviations from safety protocol are breached (W1) also achieve the goal of visual management. Another way of achieving visual control is by making invisible attributes of the process visible through measurement (Stalk & Hoult, 1990). C1 enables this by displaying environmental attributes that supports the productivity through worker comfort. Any deviations of environmental attributes such as extreme weather will be alerted to relevant management personnel to stop the activity temporarily (Yi et al., 2016). Despite stoppages increase cycle time, it is a necessary stoppage to reduce future variability (Shingo, 1986).

The transparent and documented nature of the digitalized visual management systems also enhances awareness of personnel to re-evaluate the safety standards that are being implemented. S2 requires the site to detect installation status of fall prevention equipment in every potential fall risk (Khan et al., 2022). W1 checks the PPE compliance status of every worker on site (Delhi et al., 2020). W2 detects abnormal posture and vital signs of workers (Kim and Cho, 2020), enabling iterative redesign of work methods, break schedules, or task allocation. In addition, as stated before that C1 monitors structural stability through measurements of any

deformations, displacements, and alarm history data. These examples will enable evaluation of compliance in safety standards and drives continuous improvement (P9) or philosophically called *Kaizen* (Imai, 1986).

DIGITAL SAFETY FUNCTIONS THAT SUPPORT LEAN PRINCIPLES

On the other hand, the digital safety functions that achieves the greatest number of lean principles are C1 and M1. C1 achieving P1, P3, P4, P5, P7, P9 has been discussed earlier. Temporary support structures such as scaffolding, tower cranes, or retaining walls provide the platform for workers to perform their activities and even do corrective work as late in the process as possible. By monitoring the integrity of these structures and verifying that environmental conditions remain within comfortable range, these functions support process flexibility (P6) and control (P8), helping maintain stable productivity (Koskela 2000, Stalk & Hout 1990). Furthermore, it supports conversion and flow improvements. If structural defects are detected, it can stimulate improvements in installation standards of other structures in the construction site. At the same time, it supports flow improvements by monitoring the stability of temporary structural such as scaffolding, which is a platform to support conversion activities. Hence, the function balances flow and conversion improvements (P10).

M1 is a unique function in digital construction site. With the systematic and integrated nature of the function, it provides a platform for comprehensive safety management of the construction site (Guo et al., 2013). Pedó et al. (2023) has specifically analysed similar mechanism and concluded enhanced transparency and continuous improvement of operations. This mechanism requires that all safety-related data are centralized and visualized for monitoring and querying purposes. Real-time data can be used to plan and manage necessary proactive measures to prevent non-value activities from happening. This function embodies the lean principles that the other safety functions embody.

The rest of the safety functions achieves roughly the same number of lean principles and didn't really have a big gap with C1 and M1. It can be inferred that all the functions serve the same purpose, which is to reduce incident and its related outcomes. Since their approach comes from different perspective, one focusing on site-related hazards and the other focusing on worker safety, hence why some embody different lean principles than others. But ultimately, most of the function embody lean thinking by integrating digital technologies with platforms and mechanisms for querying/visualizing data, enabling for continuous improvement and issuing near real-time action. All in all, adding value in the form of safety performance and making the construction process leaner.

To give a perspective on the differences, we will take P6 (Increase output flexibility) for examination. The functions of S1 and S2 are related to site security and identification of site-related hazards. Checking and verifying personnel qualifications to prevent intruders does support reducing variability (P3), cycle time (P4), control over the complete process (P8), etc., but it does not have characteristics that increases output flexibility (P6). Alternatively, W2 focuses on identifying health risk on active workers. By monitoring abnormal posture and vital signs, it is easier for management personnel to flexibly re-evaluate the work methods or substitute the workers to gain better output.

LEAN PRINCIPLES WITH LIMITED LITERATURE SUPPORT

The least density of lean principles comes from P2 (Increase output value through the constant consideration of customer). This is not saying that safety performance is not considered as value, but according to Koskela (2000) added value is more commonly known as a conversion process: materials to product, and only conversion activities add value. Hence it can be inferred that safety prevention activities are not theoretically direct enough to the meaning of value activities. For example, monitoring site environment (C1) is not a conversion process, unlike activities

such as welding, tying rebar, pouring concrete, etc, however it does support the environment for conversion activities occur to. Same theory is applied to the other functions except for M1 (Safety management system). M1 function can be tied to conversion process since it stores overall safety documentation that can be turned into an accountable and transparent safety report. This action converts information into value in the form of stakeholder's fulfilment of safety expectation (Koskela, 2000). The eleventh principle that is not mentioned in this study is "Benchmarking", the reason is that the digital safety functions simply focus on managing the technologies in the construction site instead of comparing performance with the best practices from other organisations.

DISCUSSION

By observing the matrix, the deployment of digital technologies may require consideration in management practices for careful targeted operational conditions. The main lean principle is elimination of waste (Koskela, 2000). This means the deployment of safety technologies must maximizes on reducing non-value-adding activities (P1), or in safety terms "accidents", which will positively affect P3 (reduce variability) and P4 (reduce cycle time). For example, a detection camera used to monitor fall prevention measures must ensure that all areas where workers operate are visible, without leaving any area unmonitored. Also, ensure that material flows are well managed so that it wouldn't obscure visibility (P7: transparency) and making sure selection of camera accuracy for adequate detection capability. Then, allowing this monitoring to be visible and documented for management personnel to assess the installation deviations will stimulate improvements in the future (P9). The same concept can be applied to other safety functions, such as C1, by ensuring that measurement tags are applied in all designated structures. Another, W1 and W2 require adequate coverage of worker health data and location-related risks, without major blind spots. From this perspective, the benefits of the safety technologies will be maximised while reducing inefficiencies and making the process leaner.

Lastly, it is crucial to note that in implementing lean practices through these technologies to promote safety performance on construction sites relies on the company to develop lean thinking (Gambatese et al., 2017). Deploying safety technologies without thinking in lean fashion does not necessarily remove waste in an efficient manner. For example, installing a certain number of PPE compliance detection camera, where it leaves a certain area or angle of the site unmonitored, does not embody lean thinking where visual management is key. False alarms and excessive maintenance may disrupt workflow and increase cycle time. Furthermore, incorporating the digital safety system into daily huddle meeting and doing PDCA cycles, as well as employee digital operation training, will eventually bring best practices. Hence why it is important to align lean thinking when implementing safety technologies on construction sites. However, it is also important to acknowledge the barriers for digitalization in this industry. The barriers aren't always related to the technological operation, but management-related issues such as high costs, commitment, and recognized benefits are factors to be considered. Ample efforts have been done to identify numerous digitalization barriers from case studies (Bajpai & Misra, 2021). Hence, evaluating the organization's own capability and overcoming critical bottlenecks for digitalization will be vital to proceed with successful implementation.

LIMITATIONS

There are several limitations in this study. First, it is important to note that the matrix is for a theoretical exercise and no extensive validation is conducted for the framework. Second, considering the limited research efforts of lean in the construction industry as compared with the manufacturing industry, let alone in construction digitalization, there are relatively limited

lean digitalization studies to support the matrix. However, as present, this literature pool is enough to achieve the goal of the study, which is to serve the purpose of exploring the alignment of safety digitalization with lean principles.

CONCLUSION

Lean construction and emerging digital safety technologies have developed from different perspectives, yet they share the common goal of improving both safety performance and overall construction productivity. While this study adopts lean principles as the analytical lens, the practicality of digital safety functions is not limited to projects that explicitly implement lean construction. Many of these functions may also support overall project and safety improvement in conventionally managed projects, however, the lean perspective helps clarify how their implementation can further reduce waste, and the act of simply acknowledging this mechanism can improve its performance. Through the identification of 44 potential interactions, the framework provides a theoretical foundation for understanding the alignment between these two paradigms and illustrates how the implementation of digital safety technologies can embody lean principles to enhance safety outcomes. The findings suggest that abundant synergies exist between the two paradigms, offering opportunities to achieve greater benefits than implementing each independently.

The interactions identified in this study are presented as theoretically grounded hypotheses, which remain open for further empirical validation. As such, the study contributes to constructive research by offering a structured framework for analysing the integration of lean principles and digital safety technologies. For researchers, this framework provides a basis for testing and verifying the proposed interactions through future empirical studies. For practitioners and project designers, the framework offers guidance for planning, selecting, and managing the implementation of digital safety technologies in a manner consistent with lean construction objectives, thereby maximizing their combined impact on site safety and operational efficiency.

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