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Doctoral research in construction management

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Using Real-Time Indoor Resource Positioning to Track the Progress of Tasks in Construction Sites

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Lean construction methods have demonstrated potential to improve construction productivity. For example, the location-based management system and the last planner system have increased the reliability of planning and control in construction production. However, these benefits are often reduced because of inaccurate manual data collection. To alleviate these problems, technologies for automated monitoring of workers have been developed to identify site events in chaotic environments. This paper aims to investigate whether a Bluetooth low-energy-based real-time indoor positioning system can monitor task progress from workers' presence. Our findings suggest that the proposed system is a feasible solution for monitoring task-level progress when there are explicit dependencies between tasks. This method could automatically detect task start and finish times and estimate the hours required to complete a task. This enables the measurement of waste hidden inside tasks, which allows for interventions for improving flows and eliminating waste.

Keywords: real-time tracking, production control, construction, Bluetooth low-energy tracking technology, task-level uninterrupted presence, task progress

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INTRODUCTION

Construction sites are often chaotic places, and any semblance of a smooth production workflow is frequently disrupted. These disruptions are often caused by the unreliable flow of work prerequisites, creating trade-offs to improvise and work under suboptimal conditions (known as making do) (Ballard, 2000; Bertelsen, 2003). These trade-offs can cause unplanned, wasteful activities, such as waiting for/after other workers, rework, and non-value-adding movements between work locations (Sacks et al., 2010). Frequent workflow disruptions also hinder a comprehensive understanding of the real-time situation on site (Sacks et al., 2010). According to the lean construction method, workflow variability is a key root cause for waste (Arashpour and Arashpour, 2015). Thus, to improve productivity and decrease waste, it is critical to measure and address variability.

Lean production principles and methods for construction production planning and control have been developed to address workflow variability (Thomas et al., 2002). For example, Takt planning and control (TPC) (Tarek et al., 2014), the last planner system (LPS), the location-based management system (LBMS), and their combinations (Seppänen et al., 2010) have demonstrated benefits in reducing the amount of non-value-adding time in construction processes, known as waste, and improving the utilization of resources (Seppänen et al., 2010, 2014; Heinonen and Seppänen, 2016).

In Takt planning and control, variability is reduced by decreasing the batch size and standardizing the process using small areas with consistent duration (Takt time) and making any deviations visible to all. To protect against remaining variability, capacity buffers are used in each Takt area. Case studies have reported improved productivity and resource utilization and reduced cycle times (Frandson and Tommelein, 2014; Frandson et al., 2015; Heinonen and Seppänen, 2016). The LPS was developed to support project teams in creating a network of commitments and reliable workflows through continuous learning and improvement, for example, by measuring the percent plan complete (PPC) and addressing any failures by using a root cause analysis (Ballard, 2000). The LBMS is used to plan continuous workflow to maximize learning effects and prevent the risk of waiting and additional mobilization. Furthermore, when data on actual production rates and labor consumption are collected, the LBMS can be used to predict and identify future clashes between tasks, which would potentially cause cascading delays (Kenley and Seppänen, 2009; Frandson et al., 2015). What is common to all these different methods is the goal of improving the reliability of construction production workflow. Progress monitoring is an essential part of these methods.

However, research has shown that the real-time data collection of accurate progress information is a key challenge in production control (Seppänen et al., 2014). First, the manual daily reporting of work progress by workers often results in incorrect judgments and human error (Goodrum et al., 2006; Costin et al., 2012). Second, direct observations by production personnel for data recording and collection are seldom able to provide useful and timely information to respond to rapidly changing site conditions (Akhavian and Behzadan, 2016). Third, the manual monitoring and progress control of construction work is resource-intensive in the context of many parallel works requiring a substantial amount of resources. For example, Kala et al. (2012) found that the full-scale implementation of the LBMS was time-consuming, resulting in an average of 9.2 h for data collection and progress reviews per week.

Decentralizing and automating progress data collection could help improve production control. Mobile applications for self-reporting the actual start and finish dates have been developed (Dave et al., 2014; Zhao et al., 2019), but workers or superintendents may not self-report accurately. Zhao et al. (2019) proposed that automated real-time progress monitoring of tasks and workers' presence could improve construction production control activities. However, their analysis focused on the accuracy and coverage of the Bluetooth low energy (BLE) system and workers' presence on the project level; a task-level analysis was left for further research (Zhao et al., 2019). The expected benefits of automated production control include (1) avoidance of errors caused by manual data collection and (2) rapid and accurate forecasts to facilitate the LBMS or other location-based methods by eliminating delays caused by manual data entry (Costin et al., 2012). Furthermore, automated progress monitoring could be used to estimate work effectiveness by looking at the patterns of workers' uninterrupted presence (Zhao et al., 2019).

In the current study, we develop and implement an indoor positioning system that tracks workers' locations to support data collection at the task level. This research aims to demonstrate the proof of concept by realizing the proposed method and expanding the discussion to other case types for elaboration in future research. Therefore, in this study, system development is confined to work locations with strict workflow dependencies. In the discussion, we address the developed method's generalizability and opportunities to adopt the proposed method in other contexts of project types. Specifically, we aim to automate the identification of task start and finish times based on heuristics to estimate the variability of work processes. For that, workers' uninterrupted presence in work locations is measured at the task level (e.g., bathrooms). The system is validated by comparing the results to original schedules and self-report progress data from workers.

TASK MANAGEMENT AND PRODUCTION CONTROL IN CONSTRUCTION

The proper management of construction tasks for the effective utilization of resources is critical for the coordinated and timely delivery of construction projects (Lu and Li, 2003). Many theories and methods regarding task planning and control in construction projects have been developed. The critical path method (CPM), which has been used since its creation in the 1950s, has benefited the construction industry in some areas, such as planning and controlling projects and communicating plans (Castro-Lacouture et al., 2009). However, researchers have called for a shift from monthly CPM schedule updates to more real-time control (Seppänen et al., 2010).

As a partial solution, location-based approaches based on weekly control have been proposed (Kenley and Seppänen, 2009) to optimize task schedule and enforce a continuous workflow (Frandson et al., 2015) by requiring details about actual crew sizes, quantities, and start and finish dates, along with suspensions for each task at each location (Seppänen et al., 2010). Typically, a weekly interval for control actions is used to ensure continuity. Researchers have also proposed focusing on look-ahead planning (make tasks ready for execution) on the specification of the hand-offs between trades, and on prioritizing the completion of tasks that require a large space for material laydown and work execution (Seppänen et al., 2013). Often, production problems are revealed only on a weekly basis (e.g., in Seppänen et al., 2013) because the chosen resolution of production control is a 1 week time frame. A weekly frequency of production control also delays the information on task progress needed to make production management decisions.

A weekly frequency is insufficient to evaluate factors impacting productivity because this requires understanding how time is spent when conducting an activity. Traditionally, productivity has been investigated with observations (Costin et al., 2012); however, human inspections and observations are tedious and not feasible for conducting continuously on a construction site due to the slow process of data collection and analysis (Akhavian and Behzadan, 2016). In order to automate tracking, researchers have explored the use of computer vision-based techniques (Yang et al., 2016; Luo et al., 2018; Konstantinou et al., 2019).

Current state-of-the-art vision-based techniques support the identification of several types of activities and the detection of task completion levels (Luo et al., 2018). The limitation of vision-based approaches is that they require large datasets for training the system (Zhao et al., 2019). Furthermore, problems of false negatives and false positives, such as occlusion, remain in state-of-the-art solutions (Park and Brilakis, 2016). It is critical to estimate the time resources engaged in value-adding and non-value-adding activities for production control purposes. In many cases, non-value-adding activities require the sensing of movement. In order to detect movement with a vision-based system, the system needs to address both detection and tracking because detection itself cannot differentiate resources of the same type. Thus, movement trajectory data are unavailable from detection-only methods (Park and Brilakis, 2016). This limitation can be solved by tracking methods. Still, the initiation of the vision-based tracking function demands the location of the tracked resources to be determined on their first appearance in the view. Therefore, compared with indoor positioning methods, the mismatch error of the tracking based on vision technologies can be propagated and affect later matching of other pairs (Zhang et al., 2018), which potentially hinders task start and finish recognition when it comes to task progress management. Also, existing vision-based tracking methods lack applicability because they usually require human operators to calibrate monitoring when encountering congestion. Construction workers often need to wear specific clothes, such as hi-vis apparel, to create a necessary tracking environment for image recognition (Konstantinou et al., 2019).

Alternatively, apart from vision-based approaches that usually rely on site cameras, mobile-based applications have been used to recognize and classify workers' activities onsite (Akhavian and Behzadan, 2016). In these instances, data collection has been conducted by embedded accelerometers and gyroscope sensors to capture the body movement of workers and enable automated activity recognition (Akhavian and Behzadan, 2016). These approaches have similar limitations, requiring large training datasets for each activity type. Additionally, they require workers to carry phones onsite at all times and keep them at adequate battery levels.

Some of these limitations can be addressed by resource positioning technologies, which allow for the automatic tracking of workers' and other asset positions. For example, the use of radio-frequency identification (RFID) (Costin et al., 2012; Park et al., 2016), magnetic field (Park et al., 2016), ZigBee (Liu et al., 2007), Ultra-Wideband (UWB) (Cheng et al., 2013), and BLE (Olivieri et al., 2017; Park et al., 2017; Zhao et al., 2017) have been successfully used to reduce data collection efforts while still assuring accuracy and providing real-time data through the automated detection of workers. For example, researchers proposed a passive RFID solution to estimate workers' travel and wait times for site elevators in a high-rise building (Costin et al., 2012). However, this research had several limitations: (1) the study did not consider the different tasks of workers; (2) researchers used the passive RFID tags, which have no self-reporting capability due to the data storage capacity of approximately 128–256 bytes; and (3) a limited detection range from 4 to 10 m, which may be further attenuated in proximity to metal surfaces (Costin et al., 2012).

Lin et al. (2013) studied a ZigBee-based tracking solution for the development of a real-time monitoring system to understand workers' behavior on large dam construction sites. This could potentially provide a task progress management of workers in practice. Using the dynamic wireless sensor network, consisting of a mesh communication tree, workers' tracking accuracy was reported to be 3–5 m. However, the study did not address the indoor construction environment. Furthermore, Cheng et al. (2013) introduced the integrated UWB (for monitoring the real-time spatial and temporal data of workers) and physiological status monitor (PSM) (for remotely tracking the posture of the workers) system to measure the proportion of the value-adding contribution of construction tasks. However, the research's objectives were to automatically detect and characterize site geometries and estimate the direct work time rate by classifying the types of workers' activities, such as wrench time, material time, travel time, and rest time. Task differences in a multi-task environment were not considered, and the research questions did not include determining when workers switched to a different task.

When compared with other technologies, BLE has several advantages in terms of the indoor tracking environment: (1) BLE technology is reliable and reasonably accurate for indoor tracking of workers, and (2) the solution is cost-efficient and easy to set up and use. In the previous study, it was demonstrated that BLE beacons are promising tracking technology for proximity detection because Bluetooth beacons are light, resistant to dynamic weather conditions, and have a satisfactory battery life with minimal false negative alerts (Park et al., 2016). In another study, where a BLE tracking solution was applied in three construction cases for project-level presence analysis of workers, it was reported that BLE beacons were cost efficient (four EUR per beacon), took half a day to install, and needed only 1 or 2 h of weekly maintenance (Zhao et al., 2019). Therefore, BLE technology could be a suitable technology for resource tracking and progress monitoring of construction works (Zhao et al., 2019). Furthermore, recent research has shown that the sensor network powered by BLE technology achieves a location accuracy of 5–10 m in construction, and the portable BLE beacons, with easy deployability and good stability (Gómez-de-Gabriel et al., 2019), enable the possibility of identifying working patterns, thus quantifying productivity (Mohanty et al., 2020). However, researchers using BLE tracking methods have not used the technology to estimate workers' task-level presence and discover opportunities for improving productivity and eliminating waste.

The concept of uninterrupted presence was proposed by Zhao et al. (2019). Uninterrupted presence as an efficiency metric is calculated when workers are continuously present in one work location without moving to another. In three case projects, the uninterrupted presence of more than 10 min in work locations was found to occur 24.5–35.5% of the time. This indicates a substantial amount of movement between work locations and a seemingly inefficient process. However, Zhao et al. (2019) did not investigate uninterrupted presence at an individual task level. Instead, they estimated an overall share of uninterrupted presence at the whole project level (i.e., project-level presence indices). With project-level data, it is impossible to identify the root causes of problems or figure out improvement interventions at the task level. Furthermore, the project-level presence indices consider the productivity of the whole project but do not consider the workflow of tasks. Specifically, the project-level presence indices did not consider the production schedule and dependencies between different tasks. A task-level measurement of uninterrupted presence opens new and interesting research questions and opportunities. For example, what is the common duration of uninterrupted presence on the level of individual tasks? Do different types of tasks have unique characteristics in terms of the variation in uninterrupted presence, which would potentially account for task inefficiency? Are workers following the production schedule (i.e., conducting the right work in the right location)? How is work conforming to planned requirements and predictions? How much buffer is included in planned work durations? Also, if it is possible to evaluate the work performed at the task level in real time, it would enable a host of new services related to the short-cycle management of construction production. Therefore, considering task and location differences, workflow-specific metrics should be studied as complementary techniques to project-level uninterrupted presence indices. This, indeed, is the motivation of this study to develop a method for task-level progress monitoring.

To achieve the objective of the study, we first need to develop a method to automatically identify the uninterrupted presence of workers at a task level and detect the actual start and finish times of tasks at work locations. Second, we propose new KPIs that will allow novel insights (such as evaluating task-level uninterrupted presence against plans for schedule conformance) to be used for better planning and production control in construction. In the current paper, we apply a real-time tracking system similar to Zhao et al. (2019) but consider an uninterrupted presence analysis at the task level while using positioning data to monitor task progress. For this, we propose the following research questions:

(1). Can indoor positioning data be used to enable the automatic detection of the start and finish times of construction tasks?
(2). Does the uninterrupted presence at a task level provide new insights that can help identify and develop interventions for better production control in construction?

MATERIALS AND METHODS

Research Process

We use the design science research methodology; the process of this research is divided into six stages (Peffers et al., 2007). **Table 1** summarizes the main stages and key aspects of the stages. The first three stages are related to comprehending and understanding the problem: deep comprehension of the task management and production control, identification of a problem related to the automated detection of task progress, and design and development of the solution artifact. The latter three stages are related to analysis and development: examine the applicability of the solution, implement and test the solution, and analyze the theoretical contribution of the solution.

A case study research method was selected to investigate the phenomenon within a real-life context. Case studies are suitable for answering questions of "why" or "how" (Yin, 2018). The case study method was chosen to develop the performance of a new automated task-based progress monitoring system.

For implementing and testing the solution (stage V in **Table 1**), we followed six steps to increase the reliability of the research results. The first three steps were related to setting up the system and making sure that the system performed as expected: (1) acquiring access to the initial project information and site and setting up the tracking system; (2) verifying the accuracy of the tracking system based on the ground-truth data; and (3) verifying the coverage of the system based on the ground-truth data (Zhao et al., 2019).

The following three steps, which are connected to the main aim of the current research, were related to the development of an automated method for estimating the task start and finish times based on indoor positioning data: (4) identifying the start and finish dates based on the presence information of workers in a specific work location and planning information; (5) validating the automatically estimated task start and finish dates against the self-report start and finish data by construction workers and explaining any major differences; and (6) calculating the task-level presence of workers in different tracking locations and discussing the use of a task-level presence. We used the concepts of presence indices (PIs) and uninterrupted presence threshold when conducting the estimation of task-level presence. PIs denote the share of workers' presence time of their entire operational day (from first detection in any location to last detection in any location on the same day). The uninterrupted presence threshold denotes the minimum duration that a worker must be present at one work location without interruptions to consider the presence value-adding (Zhao et al., 2019). We took the highest value (10 min) in Zhao et al. (2019) as the threshold for this case because we wanted to exclude potential non-value-adding time, such as walking around the site, as much as possible.

System Architecture

In the current research, we used the system architecture described previously by Zhao et al. (2019). Here, we briefly describe the main elements and relationships of this architecture. In this architecture (see **Figure 1**), BLE beacons that are assigned to specific workers are used to track them periodically (with approximately 1 s frequency), transmitting the media access control (MAC) address of the beacon to the gateways (Raspberry Pi) in specific locations and from gateways to the cloud. Specifically, the information on a unique MAC address of a beacon associated with the worker's profile is collected, together with the time intervals for worker presence in the database. Periodic signals in the nearby gateways capture and transmit

TABLE 1 | Summary of research methods.

Step 1: Understanding	(i) Deep comprehension of the topic	Theoretical references: lean philosophy, location-based management system (LBMS), Bluetooth low energy (BLE) indoor positioning		Case study: Plumbing renovation;
	(ii) Identify a relevant problem	1. Can indoor positioning data be used to enable the automatic detection of the start and finish times of construction tasks? 2. Does uninterrupted presence at a task level provide new insights that can help identify and develop interventions for better production control in construction?		
	(iii) Artifact	Propose how to measure the task progress information from real-time tracking so that the data can be used to automatically detect the start and finish times of the construction tasks and calculate uninterrupted presence at the task level.		
Step 2: Analysis and development	(iv) Examine applicability of the solution	Data analysis, visualization, and validation in case studies		
	(v) Implement and test the solution (case studies)	System implementation in the construction project	Data analysis and simulation (six steps)	Model refinement
	(vi) Analyze the theoretical contribution of the solution	Final version of the integrated model: system for automated task progress detection and uninterrupted time analysis to empower production control in lean construction.		

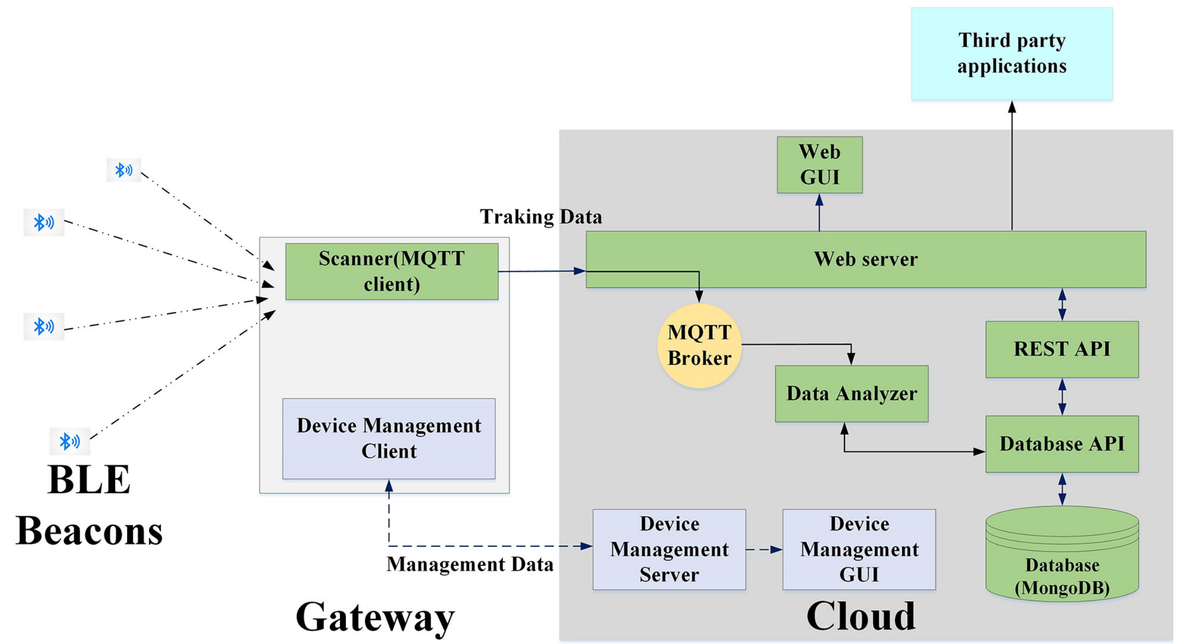

FIGURE 1 | The architecture of indoor tracking application for a construction site (adapted from Zhao et al., 2019).

those signals using the Message Queuing Telemetry Transport (MQTT) protocol. The Received Signal Strength Indication (RSSI) from the beacons is measured by gateways together with their MAC address. The broker in the cloud pushes the tracking data to the clients, and the data analyzer module subscribes to a topic published by the clients from gateways.

The data analyzer defines the location of beacons based on the magnitude of RSSI: the farther the beacons are from the gateways, the smaller the RSSI. That means the closest gateway can capture the beacon signals and determine the location of the beacon based on the event of the strongest signal (RSSI), which is compared and analyzed in the data analyzer module. The data analyzer can store the tracking data in the designed database, and a third-party application can utilize the data through a database application programming interface (API) module via representational state transfer (REST) (Zhao et al., 2019). Because RSSI is measured for closeness to the gateways, the value is dynamic under indoor construction conditions, resulting in potential flickering issues for detection. To solve this, the system utilized an array of N recent RSSI values of every beacon in every gateway, so the oldest values were pushed out when storing a new value in the data analyzer. Therefore, the last N value of RSSI is averaged, and the outlier values are eliminated from RSSI values so that the flickering problems are eased. In this study, data were downloaded from the cloud and then used for further analysis. The main elements and relationships of the system architecture

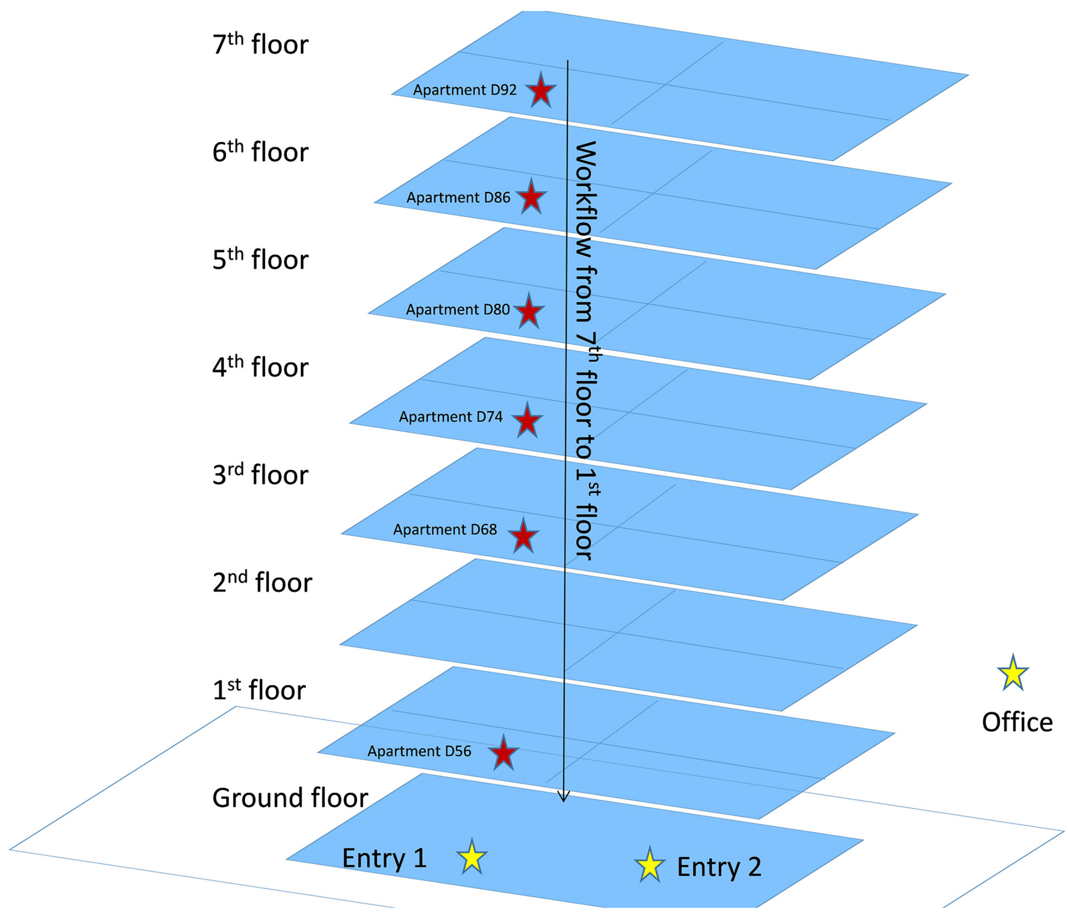

FIGURE 2 | Floor plan of the selected case study, with gateways marked.

are depicted in **Figure 1** and are adapted from Zhao et al. (2019).

Case Description: System Set-Up and Selection of Tasks

For the purpose of the present research, a residential apartment renovation project located in Helsinki, Finland, was chosen as a case for two reasons: first, this type of project (plumbing renovation) had been measured with indoor positioning technology in a previous study (Zhao et al., 2019); and second, the researchers had access to the resource-loaded task-level schedule. The indoor positioning and tracking of workers took place from March 8 to June 1, 2018. The residential building had seven floors, with four apartments on each floor (see **Figure 2**).

The BLE beacons were assigned to eight workers, who gave informed consent to participate in the study. The BLE beacons can be attached to key chains or carried in the pockets of workers, so the potential disturbance to tasks was minimal. The BLE transmission range was set to the default value of 12 meters. The placement of nine gateways is illustrated in **Figure 2**. To place the gateways, we followed the guidelines developed in our previous study (Zhao et al., 2019). Three gateways were installed at the exit locations (two on the ground floor and one in the construction site office) and one in a selected apartment on each floor (the red stars in **Figure 2**). Because the logic of the workflow was from the top to bottom floor, it made sense to track one apartment on each floor. The selected apartments on each floor were one-bedroom apartments with an area of approximately 50 m^2. The selected apartments shared the same layout; therefore, each apartment's wall structure and location were identical, which made it possible to compare the tracking data across the selected apartments. Because of the lack of required power supply for the Raspberry Pi, we could not place gateways on the second floor.

The initial system set-up took half a day. After verifying the system accuracy and coverage, the beacons were assigned to the workers, each responsible for the execution of specific tasks (**Table 2**). The construction site was visited weekly (1–2 h each time) to maintain the tracking system, for example, ensuring that the installed gateways had sufficient power supply and internet connectivity.

Table 2 summarizes the selected tasks, which can be broadly divided into two groups. First, workflow 1 (bathroom workflow) is a set of tasks with a logical sequence because of the technical dependencies in a constrained space. In the bathroom, the selected tasks had to be completed in the following sequence:

TABLE 2 | Summary of tracked workers in the selected case project.

Tasks (abbreviations)	Work trade	Workers assigned to the task
Masonry of shafts (MS)	Carpentry	Carpenter 1 Carpenter 2
Preparation of concrete floor pours and pouring (PP)	Carpentry	Carpenter 1
Waterproofing (WP)	Tiling	Tiler 1
Tiling	Tiling	Tiler 1
Joints	Tiling	Tiler 2
Suspended ceiling (SC)	Carpentry	Carpenter 1 Carpenter 3
Caulking of suspended ceiling (CSC)	Painting	Painter 1 Painter 2
Painting of suspended ceiling (PSC)	Painting	Painter 1 Painter 2
Furnishing (Fu)	Carpentry	Carpenter 1
Finishing (Fi)	Carpentry	Carpenter 1
Shaft drywall (SD)	Carpentry	Carpenter 2
Kitchen furnishing (KF)	Carpentry	Carpenter 1 Carpenter 4

masonry of shafts → preparation of concrete floor pours and pouring → waterproofing → tiling → joints → suspended ceiling → caulking of the suspended ceiling → painting of the suspended ceiling → furnishing → finishing. Second, workflow 2 (kitchen workflow) was a set of tasks that were not technically dependent on the bathroom workflow tasks but had resource dependencies, including shaft drywall and kitchen furnishing.

Overall, 12 tasks covering three trades (carpentry, tiling, and painting) in six work locations [floors 7 through the ground floor (see **Figure 2**)] were tracked, and a total of 88.95 h (5,337 min) with 1,727 time intervals were recorded. The time intervals in the tracking dataset contain information of a worker, trade, location, and the corresponding durations at that location. A new time interval was generated in the system when a worker moved to a new location and was detected by a different gateway.

System Accuracy and Coverage

To evaluate the reliability of the results, it is important to understand the positioning system's accuracy and coverage. Here, accuracy refers to the system's capability to record the trackable objects in the right location at the right time (Zhao et al., 2019). Coverage refers to how large a share of the total time the system can detect the tracked object in any location on site. To verify the accuracy and coverage, we followed the approach described by Zhao et al. (2019).

The system accuracy was evaluated based on comparing tracking results to ground-truth data. For creating the ground-truth data, two researchers walked around the site and manually recorded the time they spent in each location. Beacons were in the researchers' pockets during the accuracy tests because the same instructions were also given to workers. The researchers attempted to simulate the workers' daily routines in work locations, such as moving from floor to floor, staying in one location for some time, leaving and returning to the site from exits, etc. Then, the self-report data by the researchers were compared against the data recorded by the tracking system.

Out of 114 min of the researchers' movements, 102 min were detected in the correct location and at the right time, resulting in 89% accuracy. Floors 4 and 6 registered the most inaccurate times with 7 min (6%) and 3 min (3%), respectively. Those inaccurate minutes were registered for two reasons: (1) An incorrect gateway detected the beacon. Because the indoor environment, such as concrete walls, contributes to the complexity of real-time monitoring, thus impacting the detection of signals, some beacons could be identified by a gateway that was not closest to them. For instance, on the fourth floor, an incorrect gateway detected the beacons for 4 min 43 s. To tackle this kind of inaccuracy, it is possible to decrease the beacon signal strength, but this could lead to situations where the beacons are not detected by any gateway. (2) Data flickering is a system reliability issue in real-time tracking methods (Zhao et al., 2019). It means that multiple gateways catch the signal, and the system reports rapid switching of locations. Data flickering can be caused by the proximity of gateways to each other. On floor 4, data was flickering for 1 min 51 s (all falsely registered to the adjacent floor: floor 5). To minimize the effects of inaccuracy, we followed the guidance from Zhao et al. (2019) for a similar renovation project where the researchers proposed to place gateways in work locations enclosed by concrete walls (such as apartments) to allow for small overlapping of detection areas from nearby gateways in case of no coverage.

For coverage, the time that the researchers were detected by any gateway during the simulated time was 112 min, resulting in a coverage ratio of 98.2%. We placed all gateways in the bathroom area, and the researchers recorded their movements around the bathrooms where the workers were supposed to work. Therefore, compared with our previous study using the same tracking technology, which achieved a 71.2% coverage and 55.3% accuracy in a plumbing renovation project (Zhao et al., 2019), the current case study achieved a higher level of coverage and accuracy. However, because we were not able to place gateways on floor 2, those workers could theoretically sometimes be detected on floors 1 or 3. We did not observe a substantial amount of inaccuracy on those floors because only 1 min on floor 2 was incorrectly grouped into floor 1 during the validation period.

RESULTS

Detection of Task Start and Finish Times

The tracking system can detect the time period of each worker in a specific location. These raw data were used to estimate the actual start and end times of the tasks. This was done by implementing the following steps.

(1) Because the first task in the bathroom workflow (MS) was always scheduled one full day ahead of the first task in the kitchen workflow (SD) for each location, we started analyzing the bathroom workflow first. According to the schedule, there was a time when task PP in the bathroom was conducted at the same time as task SD in the kitchen workflow, but those two tasks were scheduled for two different workers, so their presence could be differentiated.

(2) In both workflows, the first detected uninterrupted presence on each floor was compared with the schedule of a task that was the closest to that presence, so that we could determine from which task in the workflow the worker had started the job.
(3) Task switching took place between two tasks within the same workflow. If the given task's successor was scheduled for the same worker, we assumed that the task switch happened when there was an absence of at least 4 h at that location after the last presence of the task had been detected. We used 4 h because all tracked tasks at a single location were scheduled for 4 h, except kitchen furnishing. If we could not find any absence period longer than 4 h, we took the scheduled start time of its successor and used it to search for the closest detected uninterrupted presence to determine the time of the task switch. When determining absence, we did not count the absence time outside the construction hours: (1) the workday started at 7:00 a.m.; (2) the workday ended at 3:30 p.m.; and (3) a lunch break was between 11:00 and 11:30 a.m. In this case, the task switch rule was applied on the following task sequences where the same workers were doing multiple tasks in the same location: MS-PP; WP-Tiling; CSC-PSC; and Fu-Fi.
(4) If the given task's successor was scheduled for different workers other than the one for the given task, we assumed that the task switch was happening when the first uninterrupted presence of the successor task was detected, regardless of the length of the absence time between the two tasks. This task switch scenario was applied to the following task sequences: PP-WP; Tiling-Joints; Joints-SC; SC-CSC; PSC-Fu; and SD-KF.
(5) In summary, the start time of a given task was the start of the first detected period of uninterrupted presence, and the finish time was the end of the last uninterrupted presence of that task until the task switch.

The scheduled and tracked start and finish times for the selected tasks were derived based on these task detection rules. Information related to the bathroom on floor 5 is presented as an example. **Figure 3** illustrates how the raw data on floor 5 for consecutive tasks (waterproofing, tiling, and joints in tiling trade) were used to determine the tasks' switching. Task switch 1 took place when there were 272 min of absence after the waterproof task's detected presence, which is longer than 4 h. Task switch 2 took place when the other tiler's presence was detected, regardless of the absence time length. March 24 and 25 landed on the weekend, so no presence of workers was detected.

Based on the steps, **Table 3** presents the plans and tracking results of the tasks in the sequence of how work was actually performed, from the tasks "masonry of shafts" (top) to "painting of suspended ceilings" (bottom). There is a discrepancy between the tracked and planned start and finish times. This is expected because workers do not or cannot follow their plans all the time in practice.

In summary, the presented method can begin to answer the first research question on how to automatically identify the task start and finish times based on the information of worker presence in specific locations. Next, the automatically detected information on the task start and finish times in different locations is validated against the construction workers' self-report information.

Validation of Task Times Against Workers' Self-Report Data

The validation aims to evaluate the differences between the automatically identified start and finish dates and the workers' self-report records. We are particularly interested in cases where information from the automated tracking system does not match the information reported by the construction workers and site managers. The self-report task start and finish data were collected in two different ways, depending on the workers' willingness to use a mobile application. (1) Workers self-report the information on a mobile application (SiteDrive), or (2) workers reported the information to site managers, who entered the records into the SiteDrive system.

Table 4 summarizes the differences between the system-detected results and workers' self-report results, giving a total of 11 tasks (excluding the task "shaft drywall"). We used a 4 h time difference to divide the observations into "accepted" and "not validated" categories because all the tracked tasks at a single location were scheduled for 4 h, except for the task of kitchen furnishing (3 h). Workers were supposed to enter start and finish events into the system "in real time," but some entered information later. In those cases, we expect to see some inaccuracy in the data. The natural way workers segment their time is based on breaks, which occur roughly every 2 h (i.e., morning before coffee break, afternoon after coffee break, before lunch). For this reason, we categorized 2 h (= 1 break) as "close" and 4 h (= 2 breaks) as "accepted." We considered 4 h as a limit for acceptance (= 2 breaks) and further divided the "accepted" category to "close" (2–4 h, 1–2 breaks) and "validated" (<2 h, <1 break).

In summary, the following scenarios were defined for each task for both start and finish times:

(1). If longer than 4 h, the results are considered "not validated."
(2). If between 2 and 4 h, the results are "close."
(3). If less than 2 h, the results are "validated."

Several time intervals that were "not validated" resulted from obvious errors in the progress data, self-reported by workers. For example, the task "shaft drywall" had the same self-report start and end times in all locations, and therefore, the task was excluded from the analysis. The task "masonry of shafts" on floor 1, task "caulking of suspended ceiling" on floor 3, task "painting of suspended ceiling" on floor 5, and task "finishing" on floor 1, as reported in SiteDrive, had the same start and finish times. Therefore, those tasks were also excluded from the analysis.

In summary, for the task start time, we found 35 out of 45 observations (78%) as "validated" or "close" and for the task end time, we found 27 out of 45 locations (60%) as "validated" or "close" (**Table 4**), resulting in a total of 31% of observations that were categorized as "not validated."

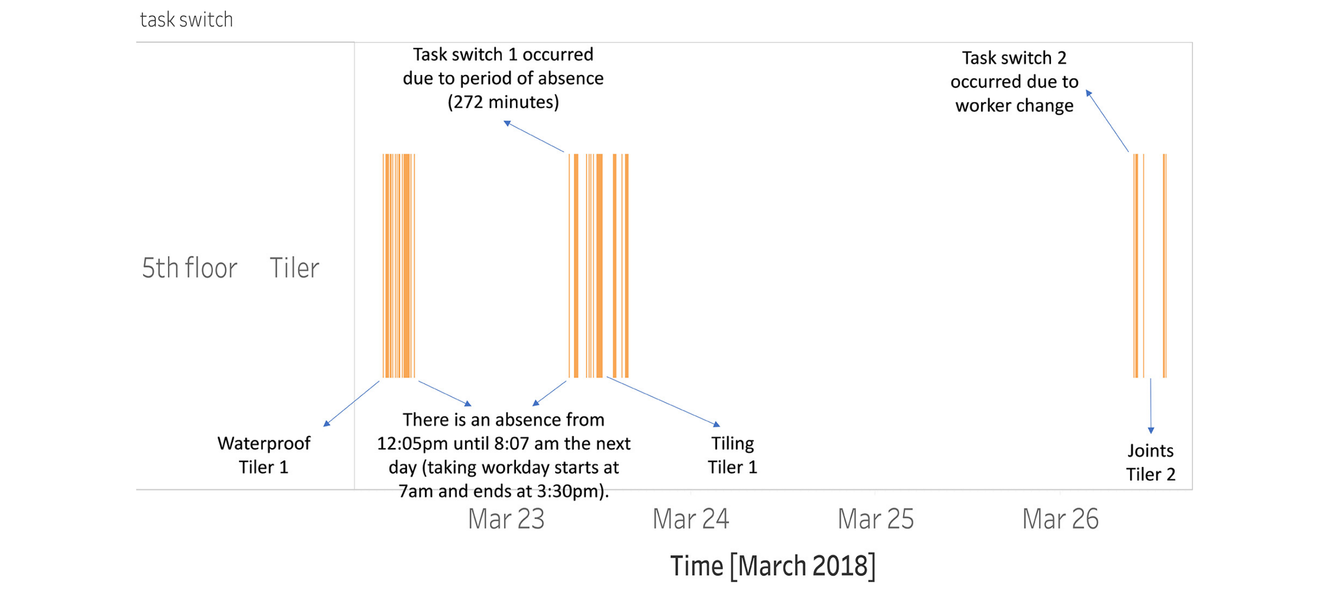

FIGURE 3 | Task switch example for three consecutive tasks on floor 5.

TABLE 3 | The scheduled start and finish time of tasks on floor 5 compared with the results based on the real-time tracking system.

Tasks	Look-ahead plan		Tracking result	
	Start time	End time	Start time	End time
Masonry of shafts	March 20 7:00	March 20 11:00	March 20 12:42	March 20 15:12
Preparation of concrete floor pours and pouring	March 21 7:00	March 21 11:00	March 21 7:31	March 21 11:04
Waterproofing	March 22 7:00	March 22 11:00	March 22 8:01	March 22 12:05
Tiling	March 23 7:00	March 23 11:00	March 23 8:07	March 23 15:55
Joints	March 27 7:00	March 27 11:00	March 26 9:31	March 27 14:38
Suspended ceiling	April 03 7:00	April 03 11:00	April 03 7:32	April 03 12:13
Caulking of suspended ceiling	April 04 7:00	April 04 11:00	April 04 7:24	April 04 10:09
Painting of suspended ceiling	April 05 7:00	April 05 11:00	April 05 7:29	April 05 9:56
Shaft drywall	March 21 7:00	March 21 11:00	March 21 7:31	March 21 13:11
Kitchen furnishing	March 22 13:30	March 23 8:00	March 22 9:50	March 23 13:06

TABLE 4 | Differences between self-report data and the tracking results of the workers (number of observations).

Task	Difference in start time			Difference in end time		
	<2 h	2–4 h	>4 h	<2 h	2–4 h	>4 h
Masonry of shafts	1	1		1	1	
Preparation of concrete floor pours and pouring	4	1		4	1	
Waterproofing	3	2	1	3	3	
Tiling	3	1	1	2	2	1
Joints		2	2	2	1	1
Suspended ceiling	4	1	1	1	1	4
Caulking of suspended ceiling	1	2	1		1	3
Painting of suspended ceiling	1		2			3
Furnishing	2		1			3
Finishing	1	1				2
Kitchen furnishing	3	1	1	2	2	1
Total	23	12	10	15	12	18

TABLE 5 | Count percentage of the recorded time intervals inside of the self-reported data of each task (the whole dataset).

Tasks	Number of time intervals between the self-reported start and finish time	Total number of time intervals	Percentage
Masonry of shafts	129	129	100%
Preparation of concrete floor pours and pouring	171	171	100%
Waterproofing	94	101	93%
Tiling	108	120	90%
Joints	33	43	77%
Suspended ceiling	67	72	93%
Caulking of suspended ceiling	217	281	77%
Painting of suspended ceiling	69	72	96%
Furnishing	25	30	83%
Finishing	94	110	85%
Kitchen furnishing	381	381	100%
Total	1,388	1,510	92%

For each of the 11 tasks, we evaluated all detected time intervals over the whole dataset to see how many of those were between the self-report start and finish times (**Table 5**). In total, 92% of the detected time intervals occurred between the task self-report start and finish times.

We made several observations based on the validation results. (1) The task start and finish times, as reported by the workers or site managers, were generally close to the automatically derived task start and finish times (see **Tables 4**, **5**). However, there were issues with the self-report data. For example, there were cases where the start time and finish time of a task at one work location were reported with the same timestamps in the SiteDrive system. This confirms that manual data collection and entry are subject to human error. (2) The self-report data represent the time range of the task execution but do not show how much time the workers were present at the work location. For example, although a worker reported the whole day for their tiling task on March 23 on floor 5, the tracking system identified several periods when no one was present. Time gaps are visible both in the handovers between tasks and inside the task execution periods. Based on the tracking data, the tasks were regularly suspended, but in the self-report data, these suspensions were not captured. Therefore, the self-report data do not give an overview of how the workers' time was actually used on site.

Next, we visualized workers' uninterrupted presence in all tasks and work locations to obtain a broader picture of the work progress (**Figure 4**). The figure demonstrates two workflows of tracked tasks in one timeline. The dashed lines separate the kitchen workflow and bathroom workflow on floors 3, 5, 6, and 7 in the figure, where tracking data for both workflows are available.

Due to several inaccuracies, we decided to exclude floor 4 from further analysis. Five out of seven tasks on floor 4 were not validated due to more than 4 h' difference between estimated and self-recorded start times. Additionally, on floor 4, we could only capture uninterrupted presence related to seven tasks out of 12, which was the fewest when compared to other floors. For tiling on floor 4, we detected only 59 min of presence for tiler 1 from 12:30 to 13:52 on March 23. According to our task detection rules, the presence was classified as "waterproofing," but tiler 1 reported doing this task on March 22 and "tiling" from 8:29 to 15:10 on March 23. Therefore, it appears that the period of uninterrupted presence was adequately related to the task "tiling," but the duration was too short when compared to the self-report task duration.

The lack of uninterrupted presence captured could result from the fact that the workers may need to remove gateway power plugs at times for their own task uses, but forgot to plug them back in straight away. This was discovered during the system accuracy test observed by the researchers, but it was not possible to estimate how long the gateways were unplugged because the system could not determine whether the undetected time was from absence of workers or gateway offline periods. On floor 4, the uninterrupted presence in six tasks (out of seven tasks detected in total) did not appear to be during the same times as the workers' self-report records. This suggests that the unplugged gateways did not capture the uninterrupted presence of workers during their self-report time range of the work, thus shortening the total captured uninterrupted presence on floor 4. Furthermore, there were also problems with workers' self-report data on floor 4 to make the real picture even more complex. For example, the tiler reported working on the task "waterproofing" on floor 4 from March 22 at 7:38 to 14:31, but there were no detected uninterrupted presences during that time on floor 4. Instead, they were detected on floor 5 from 7:31 to 11:03. However, the worker also reported the exact same period for the task "waterproofing" on floor 5; therefore, the uninterrupted presence was allocated on floor 5 and not 4. We confirmed that workers on floor 4 were not incorrectly detected by floor 3 or 5 gateways by checking that uninterrupted presence on floors 3 and 5 matched (validated) worker self-report data on those floors, except in a few special cases. However, even though in those special cases the uninterrupted presences on floors 3 and 5 did not match worker self-report data on respective floors, they either did not match worker self-report data on floor 4 or workers reported being on floor 4 at the same time as floor 3 or 5. Because this was the case, we concluded that missing data was caused by unplugged gateways and workers on floor 4 were not incorrectly detected by floor 3 and 5 gateways, and other data remains valid. For future studies, the system should be developed so that it reports unplugged gateways and the status should be monitored more frequently and corrected (e.g., 2–3 times a week instead of weekly in this case) to avoid the potential poor quality of tracking data during the test stage caused by power supply issues.

Evaluation of Task-Level Presence With Schedules

To answer the second research question regarding the possibilities of using task detection data for better production

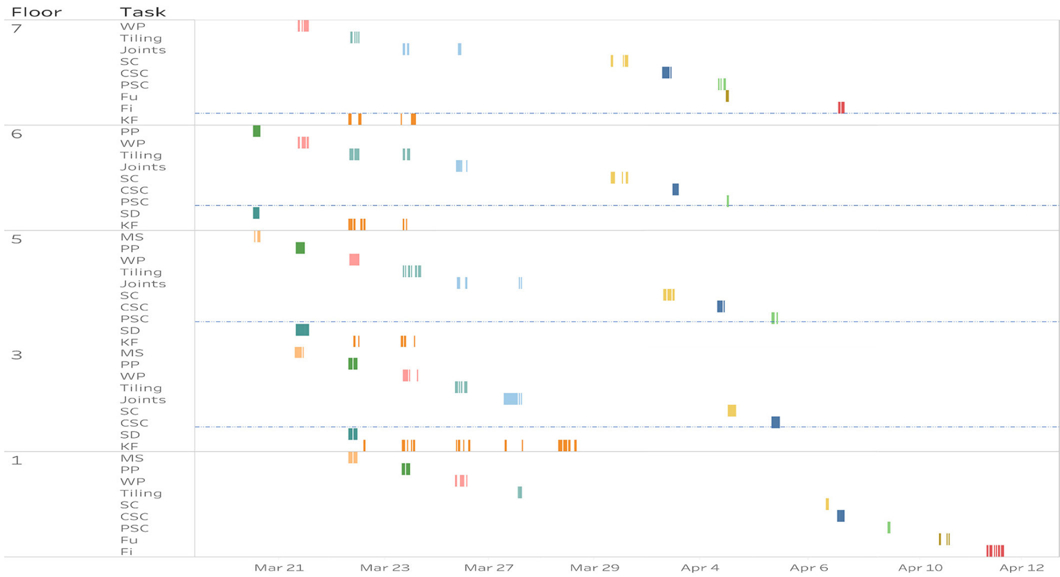

FIGURE 4 | Tracked tasks in all locations, excluding floor 4. Abbreviations: Masonry of shafts (MS); Preparation of concrete floor pours and pouring (PP); Waterproofing (WP); Suspended ceiling (SC); Caulking of suspended ceiling (CSC); Painting of suspended ceiling (PSC); Furnishing (Fu); Finishing (Fi); Shaft drywall; (SD); and Kitchen furnishing (KF).

control, we first followed the method proposed by Zhao et al. (2019) for calculating the indices for workers' uninterrupted presence for each task. The task-level presence indices (PIs) of the workers were calculated by dividing the total uninterrupted presence in a location between the start and finish times of the task by the actual duration of the task. The task's actual duration was defined as the duration between the first and last detected task times, excluding breaks and hours outside of standard working hours (evenings, weekends, and holidays).

$$\text{Task—level presence indices (PIs)} = \frac{\textit{uninterrupted presence time during task}}{\textit{actual duration of the task}} \tag{1}$$

Table 6 summarizes the results of the task-level PIs for workers in each location and the mean and standard deviation across all work locations. During the observation period, tasks were not detected or self-reported in all locations. Locations with missing data have been marked N/A (not available) in the table.

The actual duration of a task, uninterrupted presence during a task, and PIs by location and tasks indicate a significant amount of variation, even though the bathrooms were similar in terms of work quantity. High variation can also be found between the tasks. The mean presence level of all tracked tasks ranged from 21 to 65%, with a standard deviation between 2% and 28%.

As a result, we also found the phenomenon of work splitting between multiple locations. This was found in the tiling task. Although the tiler was scheduled to work on floor 7, the actual presence of a tiler in that location was very low, and they spent much of this time on floor 6 (**Table 6**). For the waterproofing task, we identified that the crews were working on floors 6 and 7 in parallel on March 21 (**Figure 5**). During the crew's operational time that day (240 min), we found that 71 min were spent on floor 7 and 107 min on floor 6, resulting in 74% of uninterrupted presence for the worker but only 29 and 45% of uninterrupted work presence in the respective work locations. Here, the look-ahead plan assumed completely finishing one location before moving to the next location.

By comparing the actual worker presence in a specific location and the expected level of presence derived from the construction plans, it was possible to identify opportunities for productivity improvement interventions. Thus, we introduce a metric to evaluate the conformance between plan and realized work:

$$\text{Presence—to—plan ratios (PPs)} = \frac{\textit{uninterrupted presence time during task}}{\textit{planned duration of the task}} \tag{2}$$

The PPs show how much presence is required compared with the planned duration to complete the task; therefore, it measures the buffer included in the task's duration to account for waste and variability. If interruptions could be completely eliminated by diminishing waste and improving the process, it indicates how much the schedule could be compressed. For instance, with a perfect flow in the task of "caulking of suspended ceiling," durations could be compressed to an average of 33% of existing planned durations, indicating opportunities for significant improvement (**Table 7**). This metric could be used to assess the task-level potential impact of lean interventions that target improving workflow, that is, by removing interruptions. Furthermore, based on equations 1 and 2, the ratio of PPs and PIs is equal to the actual duration divided by planned duration, which has been used in other studies as a metric of schedule conformance (e.g., Al-Momani, 2000).

TABLE 6 | Task-level presence indices of the workers on each floor and on average (uninterrupted presence time during task / actual duration of the task).

Tasks	Floor 7	Floor 6	Floor 5	Floor 3	Floor 1	Mean	Standard deviation
Masonry of shafts	N/A	N/A	8% (13/150)	26% (108/424)	28% (125/440)	21%	9%
Preparation of concrete floor pours and pouring	N/A	26% (142/549)	55% (117/213)	54% (114/212)	64% (129/202)	50%	14%
Waterproofing	26% (71/277)	41% (107/262)	39% (94/244)	23% (94/413)	33% (102/306)	34%	7%
Tiling	13% (30/235)	34% (132/389)	31% (143/468)	22% (71/317)	46% (30/65)	29%	11%
Joints	21% (43/208)	15% (41/267)	14% (43/315)	81% (377/463)	N/A	33%	28%
Suspended ceiling	13% (53/411)	8% (32/420)	42% (107/251)	36% (130/356)	49% (102/208)	30%	16%
Caulking of suspended ceiling	25% (53/215)	75% (116/155)	36% (120/330)	69% (287/418)	12% (41/336)	43%	25%
Painting of suspended ceiling	12% (54/456)	64% (51/80)	17% (25/147)	N/A	35% (40/116)	32%	20%
Furnishing	32% (47/150)	N/A	N/A	N/A	14% (31/225)	23%	9%
Finishing	25% (32/129)	N/A	N/A	N/A	31% (134/434)	28%	3%
Shaft drywall	N/A	91% (138/151)	46% (154/340)	59% (114/194)	N/A	65%	19%
Kitchen furnishing	26% (195/754)	28% (154/542)	22% (106/479)	25% (403/1632)	N/A	25%	2%

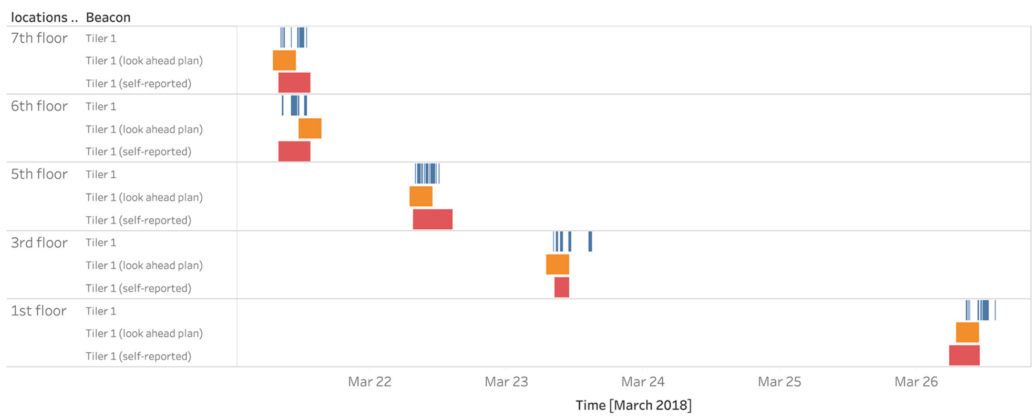

FIGURE 5 | The task of waterproofing and workers' presence visualization against the schedule and self-report records.

DISCUSSION

The results indicate that worker positioning information enables the detection of the start and finish times of tasks, providing an estimate of the task-level uninterrupted presence. This information can be further used for improving production planning and control. In this section, we discuss the generalizability of the method, the use of task presence indices (PIs) and presence-to-plan ratios (PPs), the comparison of task PIs and project-level PIs, contribution to knowledge, managerial implications, and limitations.

Generalizability of the Method to Track the Progress of Tasks

The current method relies on workflow dependencies. There are several issues that should be considered when evaluating the generalizability of the developed method. Our case study is an example of strict and confined locations where there is a process of re-entrant flow (Brodetskaia et al., 2013) and where the same workers return multiple times to the same location to perform different tasks. On the one hand, this case project is simpler than other contexts because the small locations and strict technical dependencies enable detection of a sequence of work activities. On the other hand, the workers were undertaking several small tasks, so the method included the added difficulty of determining task switch in the same person's tasks. In larger and more complex projects, the tasks are generally longer. For example, Ballesteros-Perez et al. (2020) reported that in building projects, the actual average duration for task activities is 11.35 days, while in our case, most of the tasks were 4 h. It could be argued that smaller time resolution made tracking in our case more difficult because the uninterrupted presence patterns were very short to detect.

Another feature of our project was small locations enclosed within walls, which made the tracking system accurate. In projects with large open spaces, accuracy may not be as high as in the described case. In our previous study (Zhao et al., 2019), we presented some heuristics and gateway placement strategies for open areas (roughly 30-meter intervals with a beacon range of roughly 15 meters), which can decrease the impact of open spaces on accuracy. Open spaces are also complicated in many areas of construction management. For example, in Takt planning,

TABLE 7 | Results of PIs, PPs in all tracked tasks and their ratios.

	Task presence indices (PIs)	Presence-to-plan ratios (PPs)	Actual duration/ Planned duration (PPs/PIs)
Masonry of shafts	21%	18%	86%
Preparation of concrete floor pours and pouring	50%	34%	68%
Waterproofing	34%	39%	115%
Tiling	29%	34%	117%
Joints	33%	53%	161%
Suspended ceiling	30%	26%	87%
Caulking of suspended ceiling	43%	33%	77%
Painting of suspended ceiling	32%	10%	31%
Furnishing	23%	11%	48%
Finishing	28%	34%	121%
Shaft drywall	65%	57%	88%
Kitchen furnishing	25%	57%	228%
Average	34.42%	33.83%	98%

there is an ongoing debate on how to define boundaries for locations, and methods such as work density planning have been proposed (Jabbari et al., 2020). Open spaces are challenging because any location boundaries are more or less arbitrary and there are no natural obstacles guiding the workers to follow the plan (e.g., Kenley and Seppänen, 2010). For our system, the accuracy in open spaces is noticeably smaller (Zhao et al., 2019), the system may not record the actual boundary assumed in the plan, and the boundary may shift. Accuracy problems occur, especially on the edges of work areas. In future research, the system could be generalized to open spaces by differentiating between hard technical dependencies, and "soft" planning and resource dependencies (Kenley and Seppänen, 2010). Task switch in technical dependency can be determined by assuming a start-to-start relationship and classifying periods of uninterrupted presence based on their sequence. However, it can be argued that open spaces present a challenge to any kind of automatic progress evaluation system (and indeed even for manual observation).

Precedence relationships (Benjaoran et al., 2015) and planning the sequence of activities are not unique to our case. Olivieri et al. (2019) reported that 71% of survey respondents used CPM to plan activities, and CPM includes defining logical dependencies. Some dependencies are strict and technical (e.g., walls must be built before they can be painted), while others are "soft" (Kenley and Seppänen, 2010). Several tasks can technically happen in any sequence but not at the same time because of space requirements. Expansion of our system to these more complex contexts would require the identification of hard and soft logic. Because of generally longer durations of activities and less re-entrant work in larger projects, this should not pose a difficult obstacle, and the same approach should be usable with slight modifications. Brodetskaia et al. (2013) analyzed a residential construction case of interior and finishing works for 120 apartments in 480 days. The seven activities monitored (trade activity durations varied from 1.3 to 6.9 days per apartment) were performed by five trades (drywaller, plumber, electrician, HVAC, and tiler) with just one re-entrant flow loop (the drywaller). With these longer durations and less re-entrant flow, task switch would be easier to evaluate. Thus, mapping periods of uninterrupted presence while knowing the approximate sequence of activities in each location should be enough to make reasonable progress estimates. We will validate this in future research.

In any case, it is hard for a system relying only on BLE tracking to determine when one task of the same worker finishes and the next one starts. To improve the robustness of the system in these kinds of situations, the system should include a function in the future to automatically send push notifications to workers to ask for verification whether they have started a new task or are continuing the previous task. This could enable a learning system by adjusting the assumptions of the model based on user feedback. Asking for verification could also be used to identify rework in a location, for example, if the system detects a high amount of presence in a work location where the worker's tasks have been previously finished. Nevertheless, even if we keep the single application possibility of indoor positioning system, tests with more extended periods of time, a larger number of individual workers etc., should be conducted to see if the system could be implemented in a more dynamic and complex environment.

Use of Task Presence Indices (PIs) and Presence-to-Plan Ratios (PPs) for Lean Interventions

Although the self-report information can be used to estimate the start and finish times of the task, outlining task execution boundaries or what is happening during the task is not visible using the data collected in traditional production control methods. The real-time tracking system can help reveal the actual presence of workers in the location. Based on our findings, the level of uninterrupted workers' presence for the task is typically low and subject to a great deal of variation. This finding provides empirical evidence for studies highlighting the high variability of the construction process (Picard, 2002; Arashpour and Arashpour, 2015).

The task PIs show that despite workers' self-reported duration of tasks to achieve completion, 43–90% of the time was spent either in other work locations than those scheduled, or they remained undetected in the scheduled location. This result agrees, for example, with the empirical research related to LPS, where the percentage of plans completed has been found to be generally low in construction (Ballard, 1997; Seppänen et al., 2010). This finding also raised another question of how much onsite presence from workers is required to complete tasks and how large buffers should be included inside the task to reach an optimal workflow.

The results of PP measurement from this study have opened a black box between the task first start and last end date on construction sites. Current construction production management approaches, methods, and techniques often overlook this in the planning and control of construction production. Although LBMS forecast calculations are critically impacted by task suspensions (e.g., Kenley and Seppänen, 2009), in practice, data are typically not entered into any system, which was also illustrated by our case study where no interruptions were entered by workers.

In the current study, we calculated PPs to show how much the presence of different tasks is required to complete the planned score. The remaining portion of task duration can be considered a buffer required to account for waste and variability. Therefore, this metric could be used to assess the task-level potential for lean interventions on that particular task. PPs suggest the minimum duration in which the task could be completed if wasteful interruptions were eliminated. On average, in our case study, just 34% of task durations were needed for actual work, indicating a considerable improvement opportunity if perfect or near perfect flow could be achieved. To achieve this duration reduction, only factors causing interruptions of work need to be eliminated, which would still not consider work efficiency when workers are present in the work location.

Other studies have shown that efficiency is low (Gouett et al., 2011; Cheng et al., 2013), but our method is unable to quantify that inefficiency directly because the system does not consider the amount of output achieved by workers. Rather than making value-adding time more productive, the waste caused by interruptions may be easier to address because it does not necessarily require interventions impacting the methods of a particular work type; instead, general interventions such as improved material logistics, better work instructions for workers, and situational awareness on the worker level (Cheng and Teizer, 2013; Reinbold et al., 2019; Tetik et al., 2019) can be implemented.

The PP as a temporal indicator cannot be used to judge the actual quality of the resulting work. However, achieving a higher PP of the task at the same level of quality would be essential in future production control studies in construction. Pushing toward shorter schedules based on PP to advance lean interventions should include a prerequisite that the work's quality is not compromised. In the current study, we would like to emphasize that PP can increase by decreasing waste in the production process, ensuring more time spent at work locations. Therefore, a higher PP does not mean that a worker is hurrying to improve task performance. Instead, there are fewer interruptions, and the worker is able to spend more time at work locations. If we shorten the duration by eliminating interruptions, quality should improve. For instance, LPS for production planning and control in construction, focusing on minimizing the negative influence of variability (e.g., task interruptions) and enhancing the reliability of workflow has achieved success in improving production performance and generating a predictable workflow (Hamzeh et al., 2009). In a future study, we propose that, for example, computer vision approaches (e.g., Yang et al., 2016; Luo et al., 2018; Zhang et al., 2018) could be used to supplement our approach and system, providing means to automate the inspection of possible defects of the work. Pushing for speed at the cost of quality or vice versa is not feasible. This way, the two systems would complement each other.

The connection between PIs and PPs is presented in the results. PPs denote how much presence is required to achieve planned duration with the same productivity of tasks. PIs denote how much presence is required to achieve the actual durations. PPs have implications, such as showing how much of a buffer there is in the planned duration, while PIs are a workflow metric revealing the extent of uninterrupted time for that task. When lean interventions in construction have successfully decreased PIs, durations in future schedules can be reduced, leading to increased PPs. Furthermore, the ratio of PPs/PIs (**Table 7**) is a metric of schedule conformance: if over 100%, the task's actual duration will be longer than its planned duration. This could be measured in real time to give early warning of delays.

Compared with other flow metrics, PIs and PPs have their own characteristics and connect to other metrics in practice. For example, Hamzeh and Aridi (2013) calculated LPS metrics to explore the relationship between task anticipated (TA), a task made ready (TMR), and PPC. However, all LPS metrics are based on fully completed activities, whereas PIs and PPs allow for measurement during the progress of tasks. Seppänen et al. (2014) evaluated the impact of control actions on production rates and productivity numerically. When production rates had to be increased, this was primarily achieved by improved productivity (i.e., decreased labor consumption), which challenged the LBMS theory that control actions could mainly be implemented by adding resources. This phenomenon could be seen in real time, with increased PI values if productivity interventions were successful.

Comparison of Task Presence Indices (PIs) and Project-Level Presence Indices

Project-level PIs are used to indicate the amount of uninterrupted presence of workers on site in proportion to their daily operational work time for an overall project (Zhao et al., 2019). The project-level presence is a measure of efficiency at the project level. In a plumbing renovation project, Zhao et al. (2019) reported a project-level presence index at 25.1% using 10 min as the threshold value. In the current research, the project-level presence index was 24.8% with the same threshold, matching the previous measurements in the same project almost exactly on the project level. However, the task-level presence index was found to vary significantly between different tasks.

Compared with project-level PIs, task presence indices are evaluated based on the presence between the task start and finish dates. Because the project-level presence index considers the uninterrupted presence of all measured workers, without considering their task or specific work location, it can be considered a metric of resource flow at the project level. Because task-level indices consider task and location differences, they can additionally be used as a metric of workflow and can be used to warn management in real time of potential problems at the task level. Thus, the indices are complementary. The advantage of a project-level index is that it requires little context information, just defining the work and non-work areas. A task-level presence index requires a resource-loaded schedule and dependencies between tasks but provides information that can be used to improve the process at the task level. Therefore, both indices contribute to site production control and waste elimination from two different perspectives.

Contribution to Knowledge

The current research provides a method based on automated data collection to estimate the start and finish times of tasks and measure the task-level presence of workers. The validation of the method has shown that it can detect the start and finish dates reasonably and accurately in confined locations with strict workflow dependencies. Additionally, the method allows for seeing into the black box between the start and finish times of tasks. In the measured project, a small fraction of task duration had workers present in the work location. The system can be implemented with an inexpensive set-up, and it can retrieve automatic tracking data from the cloud.

Previous studies have not focused on investigating the possibility of automating detection of start and finish times at the task level by using the BLE tracking method. Our results indicate that automatic detection is feasible in the case of workflow dependencies in confined spaces, such as the bathrooms of residential apartment buildings. The results showed that it was possible to get good results in the selected case using a real-time tracking system in an indoor environment: here, 69% of the selected locations were validated by workers' self-report data, and 92% of the tracked time intervals fell between the self-report task start and finish dates. This indicated the robustness of the proposed approach and the system for the automated detection of task start and finish times.

The possibility of integration with vision-based approaches would improve the method to track task progress, which enables extended contribution in future studies. For example, Zhang et al. (2018) proposed a method from camera views that can be used to match construction site resources such as workers and equipment. This method is useful for identifying workers' site activities from different camera views and automatically matching them, therefore providing possibilities for dynamically tracking the workers' continuous workflow. However, despite good research results, the study still left room for further exploration of using matched visual appearances under different camera views onsite to evaluate workflow qualities, such as proposed task-related KPIs. In addition, Yang et al. (2016) studied vision-based worker action recognition based on a proposed Bag-of-Feature framework using a cutting-edge video representation method. The research has the potential to contribute to our study objective, since the capabilities of workers' action classification based on this vision-based approach advanced the accuracy of task progress identification and validation, therefore improving the soundness of our proposed new KPIs as PIs and PPs. Our results indicate that only an average of 34% of workers' task time was spent in scheduled work locations. It urges vision-based approaches in construction to shift focus to the time workers were actually in designated work locations rather than scanning through a full scale of video monitoring for action recognition. This provides possibilities for integrating the BLE system with a vision-based action recognition approach to improve the identification of task progress and interruptions.

Because the proposed BLE indoor positioning system relies on location information but not on action classification to determine task status, video clips need only to be analyzed when workers are detected in designed work locations. In turn, vision-based technology for action recognition (e.g., Yang et al., 2016) pinpoints workers' behaviors so that task interruptions are more accurately identified for calculating PPs and PIs, which are the main contribution of the current study. Previous attempts to empirically research production at the task level have been reported as related to mainstream CPM scheduling (e.g., Senior, 2007; Castro-Lacouture et al., 2009), LBMS (e.g., Seppänen and Kankainen, 2004; Seppänen, 2009, Seppänen et al., 2014) and LPS (e.g., Ballard, 2000). Although LBMS studies have tried to manually account for the suspension of tasks to get more accurate production rate data at a daily level, studies based on CPM and LBMS have mostly focused on comparing the planned and actual duration and dates. However, these studies have all been conducted by looking at a week's time frame. Instead, the interruptions detected by the automated system of this paper happened continuously during implementation and were not considered by workers or superintendents in the self-reported progress information.

PPC is a metric of the LPS (Ballard, 2000), which measures the reliability of the planning process. PPC was not explicitly measured in the current study, but based on our results, it is likely that even a 100% PPC can be achieved with a relatively low presence. Existing metrics still consider the events between the start and finish times of a task (CPM and LBMS) or within a weekly plan assignment (PPC) as being a black box. More recent metrics, such as the construction flow index (Sacks et al., 2017), are also based on the start and finish dates and, thus, operate with the same limitations. Together with the tracking system, our study proposes more accurate metrics (PI and PP) for daily production planning and control of site activities.

The implications of our results are that there seems to be a lot of unrecognized waste in an activity duration. This has previously been observed with time-motion studies (e.g., Jenkins and Orth, 2004; Saukkoriipi, 2007; Kalsaas, 2010), and results related to the measurement of waste with various approaches tend to agree that the share of value-adding time averages around 25% in construction (Pasila, 2019). However, time-motion studies cannot be performed in a scalable way, so automation has been proposed by various authors. Computer vision approaches have been proposed to detect and classify workers' construction activities and thus their work performance. For example, Luo et al. (2018) proposed an activity recognition method to achieve continuous activity labels of workers onsite. With an average accuracy of 80.5%, they argued that activity recognition to implement an efficient work sampling method (Dozzi and AbouRizk, 1993) was feasible. However, these methods require extensive training datasets specific to each task, and creating a scalable method that generalizes to most of the construction work is not currently feasible. Our contribution is an automated light-weight approach, which is low cost and effortless to set up, and provides useful data related to the start and finish times of tasks and information about waste between those times, allowing for targeting lean interventions.

Managerial Implications

The proposed framework has several important implications for construction management. (1) The task-level progress tracking system can provide just-in-time information on task start and finish times. In cases where obvious errors occur from workers' self-report records, the tracking data are a good alternative and can be automatically obtained. (2) The proposed evaluation metrics for the tasks, such as PPs and PIs, can be used to automatically raise alarms for onsite management problems in real-time, thus supporting efforts to decrease waste.

In the current project, workers or site managers manually recorded the task start and finish times in the SiteDrive information system. We found that the task self-entered progress information from five tasks was subject to manual errors. The automated data collection for tracking in real time the task start and finish times could help avoid inaccuracy and reduce the need for resources to collect control data from construction production systems.

The real-time tracking system could be an alternative for traditional human-based observations and inspections to report task progress. In our study, the concept developed for the real-time tracking of workers and the progress of tasks satisfied the accuracy requirement in most tracked tasks. There is also the potential to improve the system by adding notification features and asking whether the worker has started a task after an uninterrupted presence has been detected, rather than simply letting a worker manually enter the task start and finish dates.

Limitations

One of the main limitations of the method is the inaccurate identification of the correct duration range for some tasks. Specifically, (1) task schedules are still needed to identify the first task in each workflow or to detect a task switch when there is no absence between two tasks conducted by the same worker; (2) with this method, we cannot distinguish between several tasks done by the same person unless we define a threshold time range until the next presence appears (in this case, it is 4 h). In future research, we propose placing beacons to monitor the movement of materials that the tasks use so that more accurate identification of task switching can be made based on the interactions of tracked workers and materials. (3) In the investigated project, because the locations were small (bathrooms) and the dependencies between tasks were technical, it is reasonable to assume that the successor task could not start before the predecessor had been finished. Without technical dependencies, it may not be as easy to identify the correct task that should be performed. (4) In our validation process, we found that a small number of tasks did not match the workers' records very well. In future work, the system could ask for verification of the start and finish times from workers to resolve ambiguities.

CONCLUSION

This research has demonstrated how the proposed BLE technology-based real-time tracking system can be implemented in construction sites to detect task start and finish times based on dependencies and task schedules. The automated detection of progress information was validated against workers' self-report data. After analyzing 12 selected tasks in carpenter, tiling, and painting work trades, we learned that only an average of 34.42% of presence was needed to complete the tasks based on task PIs, and up to 66.17% of the task schedule could be compressed if the optimal workflow was reached, which shows great improvement potential in construction planning and control. Task presence indices indicate the presence level required to achieve the actual duration, while the presence-to-plan ratios indicate the presence level required to achieve the planned duration and capacities to compress the schedule. The results show that the high variability of task presences is an indication of waste. The information provides new insights that could contribute to establishing better workflows from lean interventions in construction.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article can be made available by the authors upon request.

AUTHOR CONTRIBUTIONS

JZ, OS, and AP: conceptualization. JZ and OS: methodology. JZ: data collection, data analysis, and writing—original draft. JZ, EP, OS, and AP: writing—review and editing. OS: funding acquisition. All authors contributed to the article and approved the submitted version.

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Relationship Embeddedness in Construction Project Teams: The Effect of Social Behaviors on Relational Behaviors

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Relational and social behaviors of construction project team members explain relationship embeddedness. The literature review revealed three social behaviors (i.e., past experience, benevolence, and integrity) and seven relational behaviors (i.e., harmonization of conflict, propriety of means, restraint of power, reliance and expectation, contractual solidarity, flexibility, and reciprocity) commonly exhibited by construction project team members. Through a binomial logistic regression, research findings revealed that past experience was a significant ($p < 0.01$) predictor for five of the seven relational behaviors while benevolence and integrity were each significant ($p < 0.01$) predictors for three of the seven relational behaviors. Overall, out of the seven relational behaviors, only propriety of means is predicted by all the three social behaviors. Through internal validation, the prediction models performed well based on both positive predictive values and negative predictive values. From a relationship management standpoint, this research introduces relational and social behaviors of team members as triggers of relationship embeddedness. The results contribute to understanding the effect of social behaviors on the relational behaviors found in construction project teams where eleven statistically significant models that predict relational behaviors using the social behaviors were validated. The implication of this is that construction industry practitioners can use these prediction models to predict relationship interdependencies of team members.

Keywords: social behaviors, relational behaviors, relationship embeddedness, construction, team

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INTRODUCTION

Improving construction project team relationships remains a topic of interest in construction management both in research and practice (Abdirad and Pishdad-Bozorgi, 2014; Chen, 2019), and the need to address the perennial problem of fragmented relationships in construction project teams (Alashwal and Fong, 2015; Ma et al., 2021; Hu and Chong, 2020). Team member relationships are established either formally or informally. Formal relationships are based on team member roles defined in contract documents signed by the project parties (e.g., a window installation subcontractor will depend on the masonry subcontractor to construct the proper window openings). Informally, team members interact outside their roles, which can be within the workplace or outside work environments (e.g., sporting events, family picnics, etc.). Therefore, relationships form as a result of people who have something in common (e.g., friendships arising from a commonality, relationships developing at places of work, or as neighbors). As such, individuals who have comparable attributes or behaviors are classified together, while those of dissimilar attributes are left out of the network, which can strain team relationships.

Recent research indicate that aspects of relationship embeddedness founded in relational contracts can have a significant impact on the performance of construction teams (Martins et al., 2017; Arranz et al., 2020; Dogbe et al., 2020). Relationship embeddedness can be defined as the extent of relationship interdependencies between two or more team members and considers the interpersonal relationships that team members have with one another (Sporleder and Moss, 2002). Relationship embeddedness of construction project team members shape the social interactions within the team (Rezvani et al., 2018). Social interactions are based on actions, and practices where team members are mutually oriented towards one another, and that one member's behavior will affect another. Furthermore, both relational and social behaviors of individual team members have been associated with relationship embeddedness (Sven, 2004). That is to say that construction project teams are embedded in a network of relationships which depend on the social and relational behaviors of individual team members.

Construction partnering organizations and relationship management researchers must, therefore, understand the triggers of relationship embeddedness in order to attain higher levels of construction team performance. For instance, team members' relational behaviors require the interaction and reinforcement of socially expected behaviors for the members to develop into a cohesive, high-performing team (Moran, 2005). More specifically, according to Chinowsky et al., (2010), both relational and social behaviors are central to the establishment and maintenance of sound relationships in construction teams where the relational behaviors refer to the interconnections between team members, while the social behaviors drive team relationships. What this mean is that each of these behaviors play a role in keeping the balance in team member relationships. Yet, there is a gap in research to investigate the influence of social behaviors on relational behaviors of construction team members.

The aim of this paper is to better understand the association between relational and social behaviors. To achieve this, a United States national level survey was conducted to collect information describing the respondents' opinions on the presence and absence of relational and social behavior variables. A suite of logistic regression models was fit to the reported relational (dependent variable) and social (independent variable) behaviors. Validation of the model was achieved by partitioning the data into 70% training and 30% testing datasets. The contribution of this paper is a quantitative analysis methodology to predict the probability of a relational behavior being expressed given the presence/absence of the social behavior, along with the results of the models fit with the collected data. The results of this paper provide greater insight into the role of the relational and social behaviors of construction team members in relationship embeddedness. Construction partnering organizations and relationship management researchers will find value in this paper as they work to understand how to create more cohesive and collaborative construction teams.

Relationship Embeddedness

Relationship embeddedness refers to the extent of relationship interdependencies between two or more team members and considers the interpersonal relationships that team members have with one another (Sporleder and Moss, 2002). Embedded relationships in construction project teams are exhibited when one team member holds a connection with two others who are not connected, the embedded team member acts as a "go-between," hence tying them together (Chandler and Wieland, 2010). The go-between plays a crucial role in passing information and expectations from an embedded member to unconnected members. In construction project teams, go-betweens essentially break down contractual relationships for ease of information and resource flow, which is more relational rather than transactional. The go-betweens link small groupings that exist within the network and breaks down the hierarchy that exists within the team (Chandler and Wieland, 2010). In the process, a network is formed, where members are exposed to team members' relational and social behaviors; thus, the network moves beyond individual concerns to those members of the project.

Social behaviors

Social behaviors are described as drivers of team relationships where members establish relationships based on the wellbeing of others, and members do so without expecting to be paid back (Triguero, 2018). Kereri and Harper (2019) identified social behaviors commonly exhibited by construction team members and they include: 1) previous experiences (S_1), 2) benevolence (S_2), and 3) integrity (S_3).

- Past experience (S_1): The previous experiences of team members who have worked together can influence how these members treat one another on a current project. For example, previous negative work experience may be damaging to relationships, thereby causing parties to lose trust in one another. On the other hand, a previous positive working experience may foster better relationships in a current project. As such, both positive and negative past experiences carry the potential of shaping individual behaviors of team members.
- Benevolence (S_2): Benevolence refers to one's concern for the well-being of others and to be generous or to show kindness to others. In construction project teams, a benevolent team member will show concern for the welfare of others by 1) showing consideration for the needs and interests of others; 2) acting in ways that will protect the interests of other team members; and 3) desisting from exploiting others within the team for the sake of self-interest (McAllister, 1995; Mishra, 2012). Benevolence in a team can be exhibited through such behaviors as members being willing to meet, being compassionate to one another, willingness to act in good faith, and pooling resources.

- Integrity (S_3): Integrity is defined as acting on accepted principles of right and wrong and being attentive to how one achieves results (Missimer et al., 2017). Integrity in a construction project team can be exhibited in terms of the level of blame, following through on commitments, willingness to help others, and dealing with difficult situations.

Relational behaviors

Relational behaviors stem from the well-researched relational contract theory premised on informal contracts and focused on interpersonal relationships (Harper et al., 2016). Relational behaviors exhibit a point of reference and establish standards to which parties are guided while executing specific tasks in a project. Harper et al. (2016) conducted a literature review and identified seven commonly discussed relational behaviors including:

- Harmonization of conflict (R1): In relational approaches, harmonization and conflict resolution is informal, flexible, and internal, because team members establish a distinct social order as an exchange becomes more relational (Kaufmann and Dant, 1992).
- Propriety of means (R2): Requires that team members adhere to principles of division of responsibilities, together with contract terms and conditions. Team members are to be fair in their dealings through the principle of gain share and pain share, through risk and benefit sharing (Ning et al., 2013).
- Restraint of power (R_3): It is an expectation between team members that none of the project team members will apply their legitimate authority against any other member's interest (Kaufmann and Dant, 1992).
- Reliance and expectation (R_4): Team member relationships are based on the promise that others will fulfill their part of the bargain. The expectations are anchored on the exchange of promises (Harper et al., 2016).
- Contractual Solidarity (R_5): Harmonious and peaceful state of a team that is able to preserve a relationship, especially in situations where one team member is faced with a difficult situation (Ning et al., 2013).
- Flexibility (R_6): Allows changes to occur in the environment to which the parties operate, or if the transaction exchanges between the parties are outdated, the flexibility of the team allows for termination and creation of appropriate exchanges (Macneil, 1985).
- Reciprocity (R_7): Refers to team members who treat one another as equals, and exchanges or transactions take place with these individuals being symmetrically placed. It can be said that reciprocity is a relation between individuals who mutually depend on each other's actions or influence (Macneil, 1985).

METHODOLOGY

Survey Design

A cross-sectional survey was developed to collect data to answer the research question on the relationship between relational and social behaviors exhibited by construction project team members. The questionnaire was administered through the Qualtrics online survey tool to construction project team members. The factors considered in designing the survey include open-ended vs. closed-ended, rating scales vs. ranking scales, rating scale format, order of response alternatives, question wording, and question order. After taking these factors into consideration, the questionnaire was divided into two sections for clarity, with *Introduction* section containing questions regarding personal and project information, and *Methodology* section containing questions regarding relational and social behaviors of the project team members. *Introduction* section had both open and closed-ended questions while *Methodology* section questions consisted of statement items based on relational and social behaviors of team members (**Supplementary Appendix S1**). The statement items in *Methodology* section and the general format of the questionnaire builds upon the research conducted by Harper (2014). Although the behaviors were defined, the questions that were used in this questionnaire were intentionally subjective, as people's experiences are intrinsically subjective, and the authors did not want to impart their interpretation into respondents' perceptions of these behaviors.

Questionnaire Validation

To recognize and eliminate measurement errors, the questionnaire was validated by pre-testing the questions on targeted respondents (construction management professors and qualified industry experts) to review the questionnaire reliability and consistency in responses. Qualified industry experts were qualified using the alternative point system developed by Hallowell and Gambatese (2010). After developing the questionnaire, the questions were tested with the experts. The questionnaire was sent out to these two groups via email that included a Qualtrics link. The pretesting questionnaires were analyzed for consistency. Consistency was assessed by comparing the responses from the two groups. The questionnaire was considered consistent given that the responses from the two groups were equivalent.

Structured follow-up phone interviews were conducted to gain feedback on the clarity of wording, layout and style, and the general appropriateness of the survey questions to measure and assess the targeted constructs (content validity). The researcher took notes during the interviews on any issues raised concerning the questionnaire and noted key suggestions. However, feedback was limited, and improvement of the construct validity is discussed later in this paper as an opportunity for significant future work.

The data collected from the statement items in *Methodology* section were ratings using an ordinal Likert-scale format with ratings of 1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, and 5 = strongly disagree. However, the rating scale was categorical and thus there was a need to map the responses based on the rubric attached to each question to generate the final format of the data that was ultimately used in the analysis. The rubric had contrasting scenarios; choice implying that team member exhibited both relational and social behavior, (1,1), choice implying team members exhibited relational behavior and no social behavior, (1,0), did not exhibit relational behavior but exhibited a social behavior, (0,1), and where team member did not exhibit relational nor social behavior (0,0). However, there were situations where neither the question nor the rubric did not capture any of these scenarios and was marked as N/A and were not included in the analysis. In situations where social behaviors were not explicitly stated in the rubric based on the social behavior measures, they were interpreted as implied.

Coverage errors occur when the sampling frame does not match the population investigated (Groves, 2004). This study focused on the United States construction industry; it may be assumed that the various regions and states share similarities, and thus the sample adequately represented the population. The sample size was calculated based on a margin of error of two percent assuming a 95% confidence interval and a response rate of 20–30%. Qualtrics recorded respondent locations, which were checked and showed that they were distributed throughout the United States.

According to Groves (2004), sampling errors occur due to sampling bias (when subjects within a sampling frame are not selected), or due to sampling variance (if a number of independent subjects are selected from the same sample). The simple random sampling technique used offered an equal chance for all subjects selected.

Non-response errors arise from the failure of survey respondents to respond to the entire survey (Groves, 2004). To decrease non-response errors, the survey was designed in Qualtrics so that respondents cannot proceed to the next set of questions until all current questions are answered. This "forced response" option was used to decrease non-response answers. With this study being purely academic, the author tried to make the respondents view it as such by using a university email address in sending the request to increase the rate of response. Also, the email invitation to participate in the survey was personalized (request was received as a personal email, with their name), using the Mail Merge function in MS Word/Outlook. A distribution history was exported from Qualtrics and email reminders were sent weekly to prospective respondents who had not filled out the survey after assessing recipients who had completed, started, and not started the survey. The survey was closed after the third week.

Questionnaire Distribution

The population for this study included representatives of construction project decision makers (e.g., project engineers, project managers, design engineers, superintendents, contract administrators, estimators, schedulers, field workers, and operations and maintenance personnel). The respondents to the survey were to complete the questionnaire from the perspective of an ongoing or recently completed construction project that the respondent participated in. The inclusion criteria also required that the respondents were based and working in the United States construction industry.

To develop a random sampling frame, professional organization databases listing the names and contacts of construction decision makers were used. The questionnaire was then sent to 3,207 construction practitioners, whose contact information was obtained from the Construction Management Association of America Certified Construction Manager database, the State Licensing Boards for Contractors with online registration databases (Louisiana, Texas, Ohio, Illinois, California, Pennsylvania, and Michigan), Design-Build Institute of America, and the American Institute of Architects. Of the total sent, 475 had emails that no longer worked, and ten were reported as having retired. Once the questionnaire was closed, 553 questionnaire responses (20.3% response rate) had been received, which were then used for the analysis.

Questionnaire Data Processing

Data processing started with cleaning the data by organizing participant responses using unique question identifier IDs. The responses were then assessed for completeness. The questions in *Methodology* section of the survey covering relational and social behaviors were considered as being crucial variables in the study and therefore, the authors considered responses that answered at least 19 out of the 21 (90%) questions as adequate for the analysis. After cleaning the data and checking it for completeness, 392 questionnaire responses (14.4% response rate) were used for the analysis. The relational behavior variables are represented as *Rmn*, where *m* designates relational behaviors and social behaviors are designated as S_n (i.e., S_1 for past experience, S_2 for benevolence, and S_3 for integrity). For each relational behavior, R_m, there are three variables (i.e., one under each social behavior; R_{m1}, R_{m2}, and R_{m3}).

For each relational behavior, R_mRmn, the three social behavior constructs, S_1, S_2, and S_3 were measured in contrasting scenarios that those behaviors are exhibited within a team. For past experience, S_1, members were asked how they related with others whom they worked with previously. For benevolence, S_2, varied situations in which the behavior is exhibited by construction project team members are used in the study, which are willingness for team members to meet, being compassionate to one another, willingness to act in good faith, and members pooling their resources together. Integrity S_3, on the other hand was measured by the level of blame, following through on commitments, willingness to help others, and how a respondent deal with a difficult situation. **Table 1** shows the counts of the mapped responses from the statement items in *Methodology* section.

Figure 1 graphically shows the absolute frequencies of the relational and social behavior data. The majority of survey respondents reported having exhibited relational behaviors, R_{mn} and not social behaviors, S_n (1,0). Situations where respondents reported to have exhibited social behaviors, S_n and not relational behaviors, R_{mn} (0,1) were least expressed.

Binomial Logistic Regression

Model Fitting

Binomial logistic regression which in its basic form uses a logistic function is used to model binary relational behavior (dependent variable). Additionally, many more functions exist including the one utilized in this paper as shown in **Eq. 1** where, R_{mn} is the *m*th relational behavior modeled as a function of S_n, which is the *n*th

TABLE 1 | Absolute frequencies for relational and social behavior data.

Relational behavior, R_m		(R_{mn}, S_n)				
		(0,1)	(1,1)	(1,0)	(0,0)	Total
Harmonization of conflict	R_{11}, S_1	4	99	229	43	375
	R_{12}, S_2	0	3	343	46	392
	R_{13}, S_3	161	1	77	77	316
Propriety of means	R_{21}, S_1	2	114	215	44	375
	R_{22}, S_2	6	97	203	52	358
	R_{23}, S_3	3	73	238	49	363
Restraint of power	R_{31}, S_1	11	50	63	63	187
	R_{32}, S_2	6	0	349	0	355
	R_{33}, S_3	2	85	243	42	372
Reliance and expectation	R_{41}, S_1	2	96	228	54	380
	R_{42}, S_2	5	36	196	98	335
	R_{43}, S_3	3	60	223	74	360
Contractual solidarity	R_{51}, S_1	4	41	232	82	359
	R_{52}, S_2	5	75	199	68	347
	R_{53}, S_3	6	57	237	60	360
Flexibility	R_{61}, S_1	1	60	247	59	367
	R_{62}, S_2	4	37	259	66	366
	R_{63}, S_3	20	7	116	185	328
Reciprocity	R_{71}, S_1	1	83	223	67	374
	R_{72}, S_2	1	227	21	0	249
	R_{73}, S_3	0	143	142	13	298

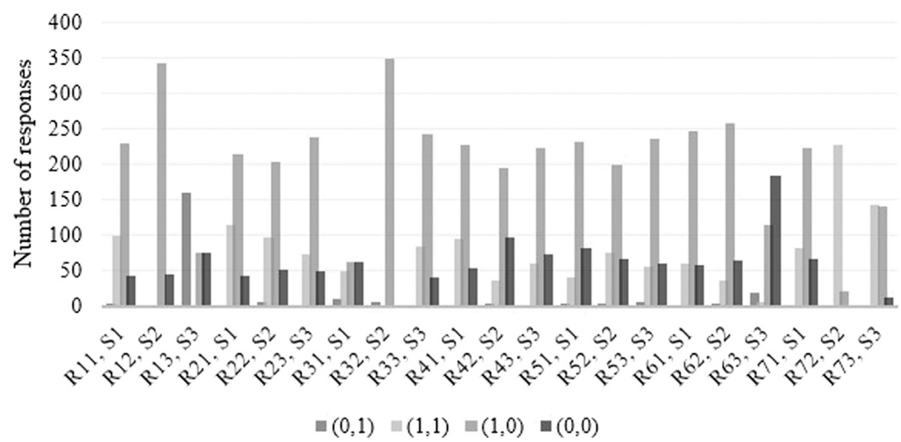

FIGURE 1 | Absolute frequencies for relational and social behavior variables.

social behavior. The index variable m ranges from 1 to 7 and n ranges from 1 to 3, corresponding with the behaviors previously described. The social behavior S_n is binary, with a null value indicating it is not expressed and a value of unity indicating it is expressed. The probability $P(R_{mn} = 1)$ is the probability of that the relational behavior is expressed (i.e., the value of this variable is unity), as opposed to a null value, indicating it is not expressed. Regression coefficients β_0 and β_1 are determined by fitting this model structure to the collected data. Given the three social behaviors and seven relational behaviors, 21 models were fit.

$$P(R_{mn} = 1) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 S_n)}} \quad (1)$$

After fitting the collected data to the model in **Eq. 1**, logistic regression coefficients and overall models are tested for statistical significance. Significance tests are based on standard errors associated with the logistic coefficients and p values are used to test the null hypothesis that the logistic coefficient is zero (0), indicating that there is no statistically significant correlation between social and relational behaviors.

Model Interpretation

Logistic regression coefficients are in log-odds units and cannot be interpreted in the same way as regular ordinary least squares (OLS), posing a challenge in their interpretation. Therefore, regression coefficients are often converted to odds using **Eq. 2**

(Statistical Consulting Group, 2016). When $S_n = 1$, indicating that the social behavior is expressed, the odds are calculated as shown in **Eq. 3**. When $S_n = 0$, indicating that the social behavior is not expressed, the odds are calculated as shown in **Eq. 4**. The odds ratio (OR), shown in **Eq. 5**, is then calculated by comparing the odds of the two states ($S_n = 0$ and $S_n = 1$). The odds ratio indicates how much more likely it is that the relational behavior is expressed when the social behavior is expressed, compared with when it is not expressed. Note that **Eq. 5** can also be expressed as the exponentiated value of the logistic coefficient, β_1.

$$Odds(Rmn = 1) = e^{(\beta_0+\beta_1 S_n)} \tag{2}$$

$$Odds(Rmn = 1)S_{n=1} = e^{(\beta_0+\beta_1)} \tag{3}$$

$$Odds(Rmn = 1)S_{n=0} = e^{\beta_0} \tag{4}$$

$$OR = \frac{e^{\beta 0+\beta 1}}{e^{\beta}0} \tag{5}$$

The 95% lower confidence interval (LCI) and upper confidence interval (UCI) for the odds ratios, collectively called OR 95% CI, are calculated in accordance with **Eq. 6**, where S.E.β1 is the standard error of the estimated model coefficient β1.

$$\text{OR 95\% CI} = e^{[\beta 1 \pm 1.96*S.E.(\beta 1)]} \tag{6}$$

Predicted probability values calculated in accordance with **Eq. 1** when $S_n = 0$ and when $S_n = 1$, can be compared using relative probability (RP) as shown in **Eq. 7**. Similar to odds ratio, when relative probability is greater than 1, it means that a team member who exhibit a social behavior being associated with a relational behavior of another is higher than the probability of those who do not exhibit social behaviors.

$$RP = \frac{P(R_{mn} = 1|S_n = 1)}{P(R_{mn} = 1|S_n = 0)} \tag{7}$$

Model Goodness of Fit

The Pearson and deviance chi-square tests are often used to evaluate the goodness of fit of OLS regression models. Pearson and deviance chi-square tests are based on the minimization of squared differences between predicted and observed values, a condition that is not applicable for logistic regression. In their place, pseudo R-square (R^2) goodness of fit measures are used. Pseudo R^2 statistics commonly used are McFadden, Cox and Snell, and Nagelkerke R Squares (Allison, 2014). Cox and Snell R^2 has a score of less than 1, and therefore, Nagelkerke's pseudo R^2 adjusts this deficit to make it cover a full range from 0 to 1 (Chan, 2005). Nagelkerke's pseudo R^2 (RNK2) is calculated using **Eq. 8**, where RCS2 is Cox and Snell's Pseudo R^2 and RMAX2 is explained in **Eq. 9**, where n is the sample size, and LL represents log-Likelihood for the null model. The closer Nagelkerke's pseudo R^2 is to 1, the better the logistic regression model fits (Liao, 2000).

$$R^2_{NK} = \frac{R^2_{CS}}{R^2_{MAX}} \tag{8}$$

where

TABLE 2 | Binary classifier outcomes.

		Predicted	
		0	**1**
Observed	0	TN	FP
	1	FN	TP

$$R^2_{MAX} = 1 - \exp\left[2\left(n^{-1}\right)LL(0)\right] \tag{9}$$

Model Validation

Statistical prediction requires that the models be validated, as validation gives prediction models credibility that the resulting output would occur given similar input variables. In other words, robust model validation at a specified confidence level offers credibility that the prediction model results can be relied upon. Prediction performance for logistic regression is evaluated through internal (e.g., data splitting) or external (i.e., new data) validation. For this paper, the models are internally validated by partitioning the original data into 70% training and 30% testing datasets. Thus, the models are fit on 70% of the data (274 responses), while 30% of the data (117 responses) was retained (i.e., not used for fitting) to validate the model on new data.

Statistically significant models were tested for prediction performance using a confusion matrix (Steyerberg et al., 2010). In constructing the confusion matrix, the predicted probabilities of team members' relational behaviors given the social behaviors is calculated using **Eq. 1**. Then a cutoff/classifier, pmn* is determined as a number that lies between the two probabilities (i.e., probabilities calculated when $S_n = 0$ and when $S_n = 1$). If the estimated probability is greater than this cutoff/classifier, 1 is assigned, otherwise 0 is assigned. A two by two table, as shown in **Table 2**, is formed by counting the four outcomes of the binary classifier:

- True positive, which represents positive subjects that are classified as positive (TP)
- False positive, which represents incorrect positive prediction (FP)
- True negative, which represents negative subjects that are classified as negative (TN)
- False negative, which represents incorrect negative prediction (FN)

The models are characterized by accuracy (**Eq. 10**), sensitivity (**Eq. 11**), and specificity (**Eq. 12**) performance metrics. The accuracy of a prediction model is its ability to correctly differentiate the relational behaviors influenced by social behaviors and those that are not. Sensitivity of the prediction models is their ability to determine relational behaviors correctly, whereas specificity is the ability of the prediction models to determine the social behaviors correctly. Perfect accuracy, sensitivity, and specificity are demonstrated when these values equal unity, while a value of zero is the lowest that can be calculated.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (10)$$

$$Sensitivity = \frac{TP}{TP + FN} \quad (11)$$

$$Specificity = \frac{TN}{TN + FP} \quad (12)$$

Accuracy is the ratio of correct predictions to total predictions made. The higher the accuracy, the better the prediction model. Sensitivity and specificity are useful if the values are high. High sensitivity values indicate that it is unlikely that the prediction models will predict that there is a relationship between relational and social behaviors when indeed there is no relationship, while low sensitivity values indicate the prediction models will have a high false negative rate. High specificity values mean that the prediction models are unlikely to predict a false relationship between relational and social behaviors when there is no relationship, while low specificity values indicate that the prediction models will have a high false positive rate.

The applicability of sensitivity and specificity has strong limitations. For example, sensitivity is only useful for deciding that a negative outcome of an analysis is so unusual that it strongly indicates the absence of the situation under investigation. This means that sensitivity analysis is only useful when these values are high. On the other hand, an analysis with high specificity is useful only for deciding that a positive outcome of an analysis is so unusual that it strongly indicates the presence of the condition under investigation. For meaningful interpretation of these metrics, both sensitivity and specificity values need to be high. Unfortunately, when sensitivity is low, specificity is high and vice versa because models with high sensitivity often come with fairly high rate of false positives. As such, Positive Predictive Value (PPV; **Eq. 13**) and Negative Predictive Value (NPV; **Eq. 14**) metrics are also calculated to aid in interpreting validation results of prediction models, with values ranging from 0 (worst) to 1 (best). High PPV is desirable, meaning that false positive results are minimized during the analysis. Moderate PPV may also be acceptable if follow-up studies are permitted. Similarly, high NPV is desirable, meaning that false negatives are minimized during the analysis. Moderate NPVs may also be acceptable if the prediction models are based on a follow up study for a known condition.

$$PPV = \frac{TP}{TP + FP} \quad (13)$$

$$NPV = \frac{TN}{TN + FN} \quad (14)$$

DATA ANALYSIS AND RESULTS

Sample Characteristics

The questionnaire respondents provided their current role and years worked in the construction industry as well as the number of years in their current role (**Table 3**). The profiles indicate that the respondents represent top management (e.g., vice president, construction coordinators, and program managers), middle management (e.g., senior project managers and project principals) or professional level employees (e.g., project managers, project engineers, and estimators, schedulers).

Table 3 includes not stated values for number of years in the construction industry ($n = 3$) and for number of years in the current role ($n = 4$) as these respondents left the question blank. “Other” in **Table 3** includes: owner representatives, municipality representatives, utility agencies, material vendors, program managers, task order managers, construction administrators, owner’s agents, quality assurance managers, accountable managers, vice president, design-build managers, pre-construction managers, construction coordinators, startup and commissioning manager, and project principal.

Table 4 shows that the mean number of years in the construction industry of the respondents is 26 years, while the mean number of years worked in the current role is nine years. This suggests that the respondents have substantial years of construction experience to be able to soundly respond to the survey questions.

On the construction project in which the respondents based their responses, the organizations in which they worked were responsible for the roles shown in **Figure 2**. The majority of the respondent organizations (29%) played the role of the construction manager agency, 20% of the organizations were responsible for the actual construction in the field, 10% acted as program managers, 6% each for the design team and consulting. Other roles characterized 24% of the respondents.

Project Characteristics

Fifty-three percent (208 respondents) of the respondents reported to have based their responses on completed projects, 46% (180 respondents) on projects currently in progress, and 1% of the respondents did not reveal the project status due to confidentiality of the project. These responses were included in the analysis even though project status was unknown because this data was checked against the respondent demographics such as role and number of years worked, which proved to be valid. For the projects that were ongoing (**Figure 3**), close to 50% of the ongoing projects were more than 50% complete, indicating there was sufficient time for relationship building in the projects to occur (Davis et al., 2017). The overall data was checked for outliers or some common trends of inconsistency when those that were less than 50% completed were included together with those that were more that 50% complete. SPSS software was used to check for outliers by running descriptive statistics for the overall data (i.e., mean, median, skewness, and kurtosis values). The analysis showed low standardized kurtosis and skewness values that approximate a normal distribution, meaning that there were no outliers. These responses were thus included in the analysis.

Logistic Regression Results

Model Fitting

Table 5 provides the model fitting information from the data collected through the survey. Both the relational behaviors of restraint of power and reciprocity behaviors given the social

TABLE 3 | Respondents' role and work experience.

Role	Number of years in the construction industry						Number of years in the current role				
	0–10	11–20	21–30	31–40	41+	Total	0–10	11–20	21–30	31–40	Total
Project manager	14	57	60	61	15	207	124	60	19	3	206
Project engineer	2	6	7	3	2	20	14	6	2	0	22
Design engineer	0	0	1	0	0	1	1	0	0	0	1
Estimator	1	1	3	2	4	11	4	3	0	0	7
Scheduler	2	1	0	4	0	7	6	1	0	0	7
Contracts	0	4	0	2	2	8	4	3	0	0	7
Superintendent	1	0	2	1	1	5	4	1	0	0	5
Operations	1	2	4	1	1	9	7	2	1	0	10
Other	9	41	27	35	9	121	89	27	6	1	123
Not stated						3					4
Total	30	112	104	109	34	392	253	103	28	4	392

TABLE 4 | Number of years worked descriptive statistics.

	N	Minimum	Maximum	Mean	Std. Deviation
No. of years in the construction industry	392	1.00	50.00	26.60	10.62
No. of years in the current role	392	0.40	40.00	9.65	7.50

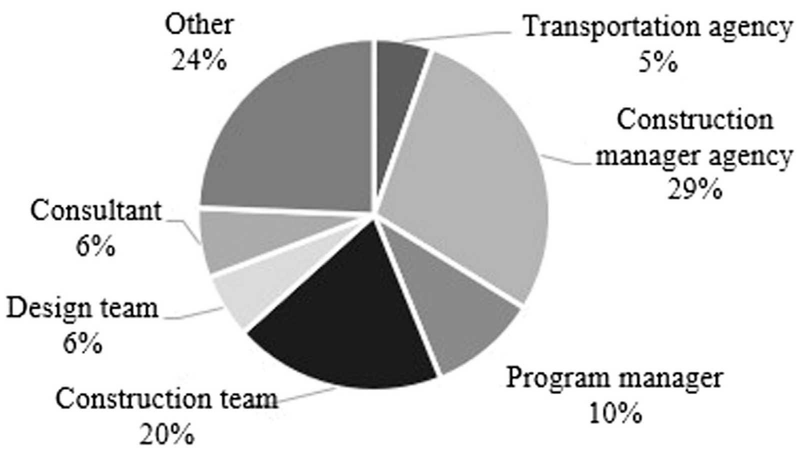

FIGURE 2 | Role of respondents' organization in the project.

behavior of integrity could not be modeled since the analysis returned a perfect fit for the data. This situation occurred because there were very few data points resulting from an issue with the questionnaire. Therefore, it was not possible to compute the standard errors and confidence intervals of the parameters. Logistic coefficients for 17 of the remaining 19 models are positive, with the coefficients for harmonization of conflict, R_1 given benevolence, S_2 and flexibility, R_6 given benevolence, S_2 are negative. Furthermore, of the 21 models, 11 that are labeled as No. 1–11 in **Table 5** had a significant slope (p-value less than 0.05), β_1 parameter, indicating a statistically significant relationship between the relational and social behaviors. One additional model was near the threshold of significance, while the remaining nine models were not statistically significant.

Non-significant models indicated that there is not enough evidence to show a relationship between relational and social behaviors. As such, moving forward with the analysis, these non-significant models were not considered for further evaluation. Also, for the two that were not modeled, estimation and further analysis was terminated because of the perfect fit of the data.

Model Evaluation

Table 6 shows the odds of $R_{mn} = 1$ when $S_n = 0$ and $S_n = 1$ as well as odds ratios and predicted probabilities and relative probabilities for the significant models. Based on the analysis, the odds ratios for the logistic regression are greater than 1. These odds ratios indicate that when project team members exhibit a

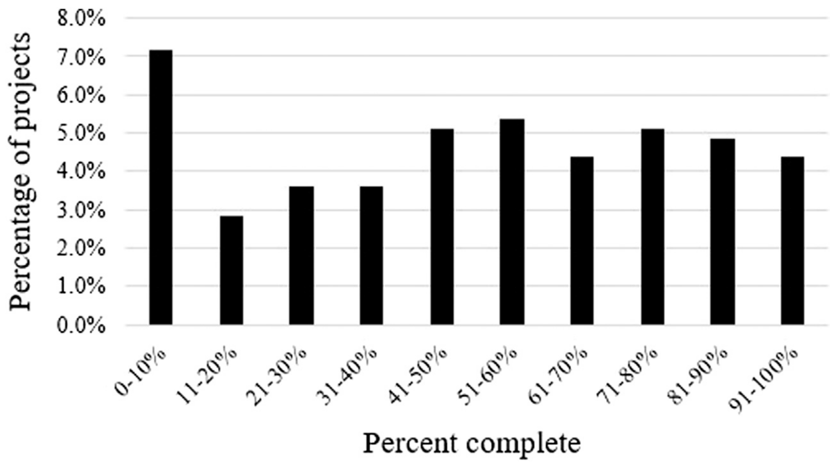

FIGURE 3 | Completion status for projects under construction.

TABLE 5 | Fitted models parameter estimates, standard errors, and *p* values.

Model	No.	β_0	S.E.	*p* value	β_1	S.E.	*p* value
$P(R_{11}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_1)}}$	1	1.74	0.20	<0.001*	1.71	0.75	0.022*
$P(R_{12}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_2)}}$		2.01	0.19	<0.001*	13.55	1,029	0.989
$P(R_{13}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_3)}}$		−0.02	0.19	0.923	−19.55	1,016	0.985
$P(R_{21}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_1)}}$	2	1.64	0.20	<0.001*	2.68	1.03	0.009*
$P(R_{22}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_2)}}$	3	1.41	0.19	<0.001*	1.19	0.50	0.018*
$P(R_{23}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_3)}}$	4	1.57	0.19	<0.001*	2.32	1.03	0.024*
$P(R_{31}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_1)}}$	5	0.16	0.21	0.459	1.08	0.43	0.013*
$P(R_{32}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_2)}}$				Not possible to model with data collected			
$P(R_{33}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_3)}}$	6	1.76	0.20	<0.001*	2.33	1.03	0.023*
$P(R_{41}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_1)}}$		1.46	0.15	<0.001*	19.74	4,060	0.996
$P(R_{42}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_2)}}$	7	0.68	0.15	<0.001*	1.27	0.55	0.022*
$P(R_{43}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_3)}}$	8	1.13	0.16	<0.001*	1.60	0.62	0.009*
$P(R_{51}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_1)}}$	9	1.04	0.15	<0.001*	1.64	0.75	0.029*
$P(R_{52}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_2)}}$	10	0.99	0.17	<0.001*	1.74	0.62	0.005*
$P(R_{53}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_3)}}$		1.44	0.17	<0.001*	0.64	0.56	0.252
$P(R_{61}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_1)}}$		1.43	0.15	<0.001*	19.77	5,146	0.997
$P(R_{62}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_2)}}$		1.40	0.17	<0.001*	0.83	0.63	0.188
$P(R_{63}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_3)}}$		−0.48	0.14	<0.001*	-0.44	0.61	0.469
$P(R_{71}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_1)}}$	11	1.20	0.17	<0.001*	2.93	1.02	0.004*
$P(R_{72}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_2)}}$				Not possible to model with data collected			
$P(R_{73}=1)=\frac{1}{1+e^{-(\beta_0+\beta_1 S_3)}}$		2.52	0.37	<0.001*	18.05	1773	0.992

Note: Social behaviors are Previous experience S_1*, Benevolence,* S_2*, Integrity,* S_3*.*

social behavior, the chance of expressing the corresponding relational behavior by team members increases by the value of that odds ratio. For example, for harmonization of conflict, R_1 given past experience, S_1, the chance of resolving issues informally increases by 5.53 times (on average) for team members who worked together previously, with an LCI of 1.28 times and a UCI of 23.74 times. Similar to odds ratio, the relative probability of a team member exhibiting a relational behavior given an exhibited social behavior is greater than one for all models.

Nagelkerke R^2 goodness-of-fit values (**Table 7**) explain the likelihood of predicting relational given the social behaviors. For example, the likelihood of predicting the harmonization of conflict behavior, R_1 given past experience, S_1 (Model 1) is 4.8%. Overall, the Nagelkerke R^2 values are low. Low R^2 values indicate that the predictor variable still provides information about the response variable but to a lower precision.

Model Validation

Table 8 shows the sensitivity, specificity, accuracy, PPVs, and NPVs of the prediction models through internal validation. The results show low values for sensitivity (11–56%), accuracy (34–44% except for model 5 with a moderately higher accuracy value of 71%), while specificity values are high (88–100%). The results also show high PPVs ranging from 86–100%, whereas NPVs are low, ranging from 18–59%.

TABLE 6 | Fitted model odds ratios with confidence intervals and predicted probabilities.

Model	Odds (S_n = 0)	Odds (S_n = 1)	Odds ratio	Or 95% CI		P (R_{mn}= 1|S_n = 1)	P (R_{mn} = 1|S_n = 0)	Relative probability
				LCI	UCI			
1	5.70	31.50	5.53	1.28	23.74	0.969	0.851	1.139
2	5.16	75.19	14.59	1.94	108.48	0.986	0.838	1.177
3	4.10	13.46	3.29	1.23	8.75	0.931	0.803	1.159
4	4.81	48.91	10.18	1.36	76.41	0.980	0.828	1.184
5	1.17	3.46	2.94	1.26	6.89	0.775	0.539	1.438
6	5.81	59.74	10.28	1.37	77.20	0.983	0.854	1.151
7	1.97	7.03	3.56	1.19	10.54	0.875	0.663	1.320
8	3.10	15.55	4.95	1.48	16.71	1.00	0.883	1.133
9	2.83	14.59	5.16	1.19	22.20	0.935	0.739	1.265
10	2.69	15.33	5.70	1.68	19.12	0.939	0.730	1.286
11	3.32	62.18	18.73	2.53	138.99	0.984	0.768	1.281

TABLE 7 | Nagelkerke R-squared goodness-of-fit.

Model	Nagelkerke R^2
1	0.048
2	0.093
3	0.076
4	0.037
5	0.071
6	0.035
7	0.012
8	0.040
9	0.025
10	0.067
11	0.085

Based on the research results that show low sensitivity values, these values are not useful in interpreting the research findings. High specificity values indicate that the prediction models have high chance of correctly predicting relational behaviors given the social behaviors of team members. High PPVs and low NPVs reveal that predicted positive expression of relational behaviors is typically correct, while the models overpredict negative/non-expression of relational behaviors given the social behaviors of construction project team members. Thus, the prediction models advanced in this paper perform quite well based on these metrics.

FINDINGS AND DISCUSSION

Results from the paper, logistic regression analysis identified a relationship between team members who exhibit relational behaviors and those who exhibit social behaviors. Statistically significant and non-significant models are shown as those supporting and not supporting the hypothesis, respectively (**Table 9**).

As shown in **Table 9**, this study finds that past experience, S_1 is a significant predictor of five of the seven relational behaviors, benevolence, S_2, and integrity, S_3 are significant predictors of three of the seven relational behaviors each. All the statistically significant models had positive and significant logistic regression coefficients, β_1, (p value < 0.05). Positive significant logistic regression coefficients indicate that the relational behavior is more likely to be exhibited when the social behavior is present, rather than absent. Similarly, it is expected that it is less likely for a team member to exhibit a relational behavior when a team member does not exhibit a social behavior.

The results of the analysis show that:

- Compared with those who have not previously worked together (past experience, S_1), those who have previously worked together were:
- 4.2 times more likely to resolve conflicts informally, flexibly, and internally (harmonization of conflict, R_1), p = 0.002.
- 11.7 times more likely to adhere to the principles of division of responsibilities together with the terms and conditions set out in the contract (propriety of means, R_2), p < 0.001.
- 4.5 times more likely to expect that members in the team will avoid applying their authority against any other team member's interest (restraint of power, R_3), p < 0.001.
- 4.9 times more likely to be in a coordinated and peaceful state that is able to preserve a relationship (contractual solidarity, R_5), p < 0.001.
- 24.9 times more likely to treat each other as equals (reciprocity, R_7), p < 0.001.
- A statistically significant relationship was not found between past experience, S_1 and reliance and expectation, R_4.
- A statistically significant relationship was not found between past experience, S_1 and flexibility, R_6.

What these findings mean, therefore, is that interactions between first time and repeat members in a construction project may not be the same. This assertion is consistent with prior research that showed that past experiences have an influence on how team members relate through the reputations established previously (Dekker et al., 2019). Therefore, previously embedded relationships will set the tone for team member expectations, which in turn provides for trust to develop and gives room for open communication and joint conflict resolution (Kululanga et al., 2002; Buvik and Rolfsen,

TABLE 8 | Prediction models internal validation metrics.

Model	Observed	Predicted		p^{*}_{mn}	Sensitivity (%)	Specificity (%)	Accuracy (%)	PPV (%)	NPV (%)
		0	1						
1	0	14	2						
	1	63	36	0.9	36	88	43	95	18
2	0	14	2						
	1	63	36	0.9	36	88	43	95	18
3	0	17	1						
	1	60	30	0.9	33	94	44	97	22
4	0	14	2						
	1	70	24	0.9	26	88	35	92	17
5	0	22	2						
	1	15	19	0.6	56	92	71	90	59
6	0	13	1						
	1	74	25	0.9	25	93	34	96	15
7	0	30	1						
	1	62	8	0.7	11	97	38	89	33
8	0	25	0						
	1	69	17	0.9	20	100	38	100	27
9	0	25	2						
	1	71	12	0.8	14	93	34	86	26
10	0	22	2						
	1	58	25	0.8	30	92	44	93	28
11	0	21	0						
	1	71	21	0.8	23	100	37	100	23

2015). For example, field personnel typically know how to work out issues informally in the field, rather than involving upper management (harmonization of conflict, R_1).

- Compared with those who have not shown concern for the well-being of others, generosity or kindness to others (benevolence, S_2), those who have shown benevolence were:
- 4.1 times more likely to adhere to the principles of division of responsibilities together with the terms and conditions set out in the contract (propriety of means, R_2), $p < 0.001$.
- 6.5 times more likely to rely on others to fulfill their part of the bargain (reliance and expectation, R_4), $p = 0.003$.
- 6.5 times more likely to be in a coordinated and peaceful state that is able to preserve a relationship (contractual solidarity, R_5), $p < 0.001$.
- A statistically significant relationship was not found between benevolence, S_2 and harmonization of conflict, R_1.
- A statistically significant relationship was not found between benevolence, S_2 and flexibility, R_6.

TABLE 9 | Significance test results for the logistic regression β_1 coefficients.

	S_1	S_2	S_3
R_1	√	-	-
R_2	√	√	√
R_3	√	-	√
R_4	-	√	√
R_5	√	√	-
R_6	-	-	-
R_7	√	-	-

Note: √ Statistically significant; - Not statistically significant.

The findings show that the relationship between benevolence and three out of seven relational behaviors exhibited by construction project team members support the argument by Ling and Tran (2012) that for a more relational team, there is a need for construction project team members to be benevolent, and desist from exploiting others to avoid conflicts. The empirical evidence in this section suggests that benevolent team members show a relationship with team members who exhibit relational behaviors aimed at supporting one another in the team. For example, benevolent team members are more likely to relate with those who are fair in their dealing through the principles of gain share and pain share. The role of benevolence behavior as it relates to relational behaviors highlights the underlying concept of social network theory that project networks are comprised of both relational and social behaviors.

- Compared with those who have not acted on accepted principles of right and wrong and being attentive to how one achieves results (integrity, S_3), those who have shown integrity were:
- 5 times more likely to adhere to the principles of division of responsibilities together with the terms and conditions set out in the contract (propriety of means, R_2), $p = 0.001$.
- 15 times more likely to expect that members of the team will avoid applying their authority against any other team member's interest (restraint of power, R_3), $p < 0.001$.
- 6.6 times more likely to rely on others to fulfill their part of the bargain (reliance and expectation, R_4), $p < 0.001$.
- A statistically significant relationship was not found between integrity, S_3 and harmonization of conflict, R_1.
- A statistically significant relationship was not found between integrity, S_3 and contractual solidarity, R_5.

- A statistically significant relationship was not found between integrity, S_3 and flexibility, R_6.
- A statistically significant relationship was not found between integrity, S_3 and reciprocity, R_7.

The relationship between integrity, S_3 and relational behaviors, R_{mn} is important in explaining team relationships in construction project networks. For example, when a team member is honest to other team members, they will adhere to the principles of division of responsibilities together with the terms and conditions set out in the contract which helps shape team relationships and thus a more cohesive team (Olkkonen and Tuominen, 2005). When members are untrustworthy and not honest with others in the team, relationship building is negatively impacted and raises tension and conflicts (Buvik and Rolfsen, 2015).

Non-significant models do not support previous research by Chinowsky et al. (2010) and Granovetter (1985) who advanced the theory that relationships constitute both relational and social behaviors under the social network theory. However, this research was exploratory and sought to establish the starting point for further investigation by researchers in this area.

Relational behaviors that show no relationship with benevolence, S_2 have a direct effect on the terms and conditions that are set out in the contract. This explains why benevolence, S_2 might be viewed as having no relationship with those behaviors. For instance, research findings do not support that benevolence, S_2 positively influence how members resolve issues and disputes, informally without involving upper management. Similarly, when team members become more benevolent, others tend to take advantage of and exploit them (Kim and Nguyen 2018). Results show that as members become more benevolent, team members are not willing to allow changes to occur in their operating environments (flexibility, R_6), treat them as equals (reciprocity, R_7), or expect that others will not exert their legitimate authority upon them (restraint of power, R_3).

Furthermore, it was not possible to model the relationship between benevolence, S_2 and restraint of power, R_3, and reciprocity, R_7, relational behaviors using the collected data. This was because of the perfect fit of the data when modeling. This might be attributed to the data collection tool or the questions that might have not been better understood by the respondents. It will be worthwhile to conduct a follow-up study using a larger sample size in a bid to model the relationship between the relational and social behaviors.

CONCLUSION

This research explores the relationship between the relational and social behaviors exhibited by construction project team members. The social behaviors, S_n include: benevolence, S_1, integrity, S_2, and past experience, S_3 whereas relational behaviors, R_m include: contractual solidarity, R_1, flexibility, R_2, harmonization of conflict, R_3, propriety of means, R_4, reciprocity, R_5, reliance, expectation, R_6, and restraint of power, R_7. These identified behaviors were used as variables in the study by means of data collected through a cross-sectional survey sent to construction practitioners across the United States. The data collected were used to model the relationship between relational and social behaviors of construction project team members using binomial logistic regression. In conclusion, the findings of this research show that:

- Past experience, S_1 predicts five of the seven relational behaviors, benevolence, S_2 and integrity, S_3 each predict three of the seven relational behaviors.
- Internal validation results show low values for sensitivity (11–56%), accuracy (34–44%, except for model 5 with a moderately higher accuracy value of 71%), and NPVs (18–59%). Specificity values (88–100%) and PPVs are high.

The insights into the concept of relationship embeddedness where the influence of social behaviors on relational behaviors of construction project teams are the main contribution to the body of knowledge. The practical implication of these findings is that the validated models showing an effect between social and relational behaviors can be considered at the team formation level as construction practitioners seek to create more integrated teams. The concept entices new directions for future research in construction project networks and collaboration in construction project teams.

LIMITATIONS AND FUTURE WORK

The primary limitations of this research were discovered during the data analysis phase. Despite efforts to ensure the construct validity of the questionnaire, it was discovered that the collected data did not map as well as anticipated to the social and relational behaviors. As explained, some behaviors had to be assumed and some answers had to be mapped as N/A because one of the behaviors was not apparent from the selection. Although the analytical procedures are sound and recommended for additional studies, significant improvements to the questionnaire should be undertaken in future work. A larger sample size is also recommended for a subsequent confirmatory study. These additional developments would add more credibility and reliability to the overall results. Further, additional research is warranted to quantify how a construction firm's bottom line is impacted by integrating behavior into team member selection impact, thus further demonstrating the importance of relationship embeddedness on project outcomes. Another area of future research is to guage the interest of contractors in understanding the effects of relationship embeddedness and project performance. An interesting future direction would be to define and set limits for the scope of the behaviors in an attempt to reducing the subjective nature of the responses from the survey. Specific case studies targeting the entire construction team is recommended to ensure that feedback is received from each and every team member.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Louisiana State University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JK designed the data collection tool, collected and analyzed the data, interpreted the results, and drafted the manuscript in consultation with the co-authors. CF led the data analysis and modeling techniques and revised the manuscript with comprehensive feedback. CH provided foundational guidance on the research topic and assisted in survey development and dissemination. IN and CH provided comprehensive feedback on the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2021.636000/full#supplementary-material

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Predictive Statistical Cost Estimation Model for Existing Single Family Home Elevation Projects

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One of the most preferred flood mitigation techniques for existing homes is raising the elevation of the lowest floor above the base flood elevation (BFE). Determination of project effectiveness through benefit-cost analysis (BCA) relies on the expected avoided flood loss and the project cost. Conventional construction cost estimates are highly detailed, considering specific details of the project; however, mitigation project decisions must often be made while considering only highly generalized building details. To provide a robust, generalized project cost estimation method, this paper implements data modeling and mining methods such as multiple regression, random forest, generalized additive model (GAM), and model evaluation and selection with cross-validation methods to hindcast elevation costs for existing single-family homes based on average floor area, increase in floor elevation, number of stories, and foundation type. Project cost data for homes elevated in Louisiana, United States, between 2005 and 2015 are used in cost prediction analysis. The statistical modeling results are compared with detailed estimations for several types of home foundations over a range of elevations. The results show substantial agreement between regression predictions and detailed estimates using RSMeans cost data.

Keywords: flood mitigation, Freeboard, cost estimation, regression, random forest, GAM, cross-validation, foundation cost

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INTRODUCTION

Elevating the lowest floor of existing homes is widely considered to be the most effective building-scale flood mitigation strategy (Bellomo et al., 1999; FEMA 2010; FEMA 2012; Li and van De Lindt 2012; Bohn 2013), in contrast to acquisition and reconstruction. In spite of the effectiveness of elevation, this construction technique is performed by highly specialized contractors and generalized cost guidance is not widely available. At the project decision stage, benefit-cost analysis (BCA) must demonstrate a positive return on investment (FEMA 2011; Orooji and Friedland 2017). Thus, reasonable cost estimates are needed for comparison with long-term benefits to evaluate the most economically efficient strategies to achieve overall mitigation goals and provide economic justification for specific projects (Renn, 1998; Amoroso and Fennell 2008).

Conventional methods for project cost estimation are unit-cost and unit-area-cost. Unit-cost is project-specific, with exact construction quantities and historical unit-price costs, while unit-area-cost is based on general building attributes such as occupancy, building type, and other building parameters. In the absence of proprietary historical cost data, RSMeans (Waier and Balboni 2018) is commonly used to estimate construction cost. However, RSMeans data do not include all necessary construction activities for elevation projects and prices can vary substantially by contractor (Gair et al., 2011). These and similar shortcomings limit the ability of stakeholders (e.g., federal, state, and local agencies, homeowners) to estimate elevation project cost effectively.

Acknowledging this issue, elevation cost guidance has been developed previously. USACE (1993) reported that for a 0.6 m (2 foot) elevation, elevating wood-frame buildings with existing pile, post, or pier foundations costs $\$280/m^2$ ($\$26/ft^2$), while elevating slab buildings costs $\$320/m^2$ ($\$30/ft^2$) in 1993 dollars. Considering a $140\,m^2$ ($1{,}500\,ft^2$) house with 0.6-m (2-ft) elevation, additional costs associated with earthen fill (slab only), landscaping, engineering design, and contract cost bring these values to $\$380/m^2$ ($\$35/ft^2$) for pile, post, or pier foundations and $\$450/m^2$ ($\$42/ft^2$) for slab foundations in 1993 dollars. FEMA (1998) reported that for a 0.6- m (2-ft) elevation, elevating frame buildings with existing basement or crawl-space foundations onto continuous foundation walls or open foundations costs $\$180/m^2$ ($\$17/ft^2$) while elevating frame or masonry slab buildings costs $\$510/m^2$ ($\$47/ft^2$) in 1999 dollars. Newer guidance has moved away from providing elevation costs, as FEMA (2012) indicates that elevation cost relates to the type of construction and existing foundation but does not provide monetary values. In each of these documents, only mean cost values are reported, limiting consideration of the distribution of cost data. Most importantly, the effect of number of stories on elevation project cost is not mentioned in existing guidance. Thus, it is clear that updated cost guidance for existing home elevation projects is needed.

Predictive statistical cost modeling has been used in several construction cost applications (e.g., Herbsman 1986; Adeli and Wu 1998; Wilmot and Mei 2005), although not specific to home elevations. To predict construction cost, Karshenas (1984) used multiple regression, Skitmore and Ng (2003) used regression and cross-validation regression, and Kouskoulas and Koehn (1974) used multiple linear regression and validated the results with two real building case studies. Lowe et al (2006) used multiple linear regression, Jrade and Alkass (2007) developed a set of linear regression models in a computer-based cost estimation program, and Sonmez (2008) used a combination of linear regression and bootstrap techniques for construction cost modeling. Additionally, Shimizu et al. (2014) used switching regression model and generalized additive model (GAM) to predict the housing price, and Liu et al. (2018) used random forest and GAM to predict construction productivity using environmental factors. Specific to natural hazard mitigation, Jafarzadeh et al (2015) applied multiple linear regression to establish construction cost models for seismic retrofit of confined masonry buildings. Although statistical cost prediction models have been used for highways, commercial buildings, residential homes, and seismic retrofits, there are no known studies for existing building elevation cost prediction.

Conventional cost estimation methods are not readily accessible to decision-makers, and existing elevation cost guidance is limited and dated. Therefore, the goal of this paper is to evaluate and improve generalized home elevation construction cost estimation using predictive statistical modeling. This is accomplished by developing a robust, generalized cost estimation method for existing home elevations. Historical home elevation cost data obtained from the Louisiana Governor's Office of Homeland Security and Emergency Preparedness (GOHSEP) are categorized statistically using 10 regression models, a random forest model, and five GAMs with 10-fold cross-validation (CV) RMSE on all tested models. The required assumptions for each model are tested and the model with minimum prediction error is selected. Prediction results are compared with costs from USACE (1993), FEMA (1998), and Gair et al (2011) after modifying and updating them for time and location.

Both the methodology and the findings from the statistical model results are contributions of this research. First, previous statistical cost prediction research has evaluated limited models such as few regressions or GAMs; however, the method proposed in this research evaluates results from three robust statistical techniques, and external prediction accuracy of the selected models are examined. Second, the results themselves offer guidance to predict home elevation costs which enhance the flood mitigation decision-making and BCA (Taghinezhad et al., 2020a). Although the model results are applicable to Louisiana, the methodology itself can be applied for elevation mitigation project cost in other construction markets. Also, if the predicted elevation costs are adjusted for time and location, they may be representative of costs expected for similar buildings in similar construction markets.

BACKGROUND

Elevation project cost varies based on several factors [**Eq. 1**], where C is the cost of the elevation project ($), A is the average floor area (m^2) calculated as the total home area divided by the number of stories, ΔE is the change in first-floor elevation (FFE, m) calculated using **Eq. 2**, S is the number of stories, and F is a categorical variable representing foundation type. The FFE elevation (NAVD88) represents the top of the lowest floor (including basement, crawl-space, or enclosure floor) from elevation certificates, where FFE_0 and FFE_1 represent the FFE before and after elevation, respectively.

$$C = f(A, \Delta E, S, F) \tag{1}$$

$$\Delta E = FFE_1 - FFE_0 \tag{2}$$

DATA

Elevation Cost Literature

USACE (1993) calculates total cost of elevation (C_t; **Eq. 3**), where C_e is the cost of elevation; C_l represents the cost of landscaping excluding trees, bushes, and flowers; C_p is the cost of professional engineering, and P_c is the contract profit percentage. Landscaping cost (C_l) is calculated using **Eqs. 4**, **5**, where A_l represents the landscaping area, C_{ul} represents the unit area landscaping cost, and W_b and L_b are the width and length of the building, respectively.

$$C_t = \left(C_e + C_l + C_p\right) \times (1 + P_c) \tag{3}$$

$$C_l = A_l \times C_{ul} \tag{4}$$

$$A_l = (W_b + 6.1) \times (L_b + 6.1)\left(\mathrm{m}^2\right); \quad [A_l = (W_b + 20) \times (L_b + 20)]\left(\mathrm{ft}^2\right) \tag{5}$$

According to USACE (1993) the cost elevation values for 0.6 m (2ft) additional elevation are as: The C_e for "wood frame building on piles, posts or piers," "wood frame building on foundation walls" "brick building," and "slab-on-grade building" are \$280/m^2 (\$26/sf^2), \$205/m^2 (\$19/sf^2), \$344/m^2 (\$32/sf^2), and \$323/m^2 (\$30/sf^2), respectively. The C_{ub}, C_p, P_c, *and* earthen fill are \$6/m^2 (\$5/yd^2), \$7,000, 10%, \$13/m3 (\$10/yd3), respectively. The slab foundation is assumed to be converted to elevated foundations; however, cost values for earthen fill are also provided. Also, it must be noted that values provided in USACE (1993) are assumed to represent 1993 dollars.

FEMA (1998) simply provides unit costs to elevate existing buildings to continuous foundation walls or open foundations by 0.6 m (2ft) of \$510/m^2 (\$47/ft^2) for frame or masonry buildings on slab foundations and \$180/m^2 (\$17/ft^2) for frame buildings with basement or crawlspace foundation, assuming 1998 costs.

Gair et al. (2011) evaluated elevation cost for typical 140 m^2 (1,500ft^2) one-story homes in Louisiana using unit-cost estimation and 2011 RSMeans residential cost data for slab and pier and beam foundations, elevated by 0.9 m (3ft), 1.8 m (6ft), and 2.7 m (9ft). However, because standard RSMeans cost data do not cover all construction activities required to elevate homes, Gair et al (2011) obtained unit cost values from a survey of foundation elevation contractors. Gair et al. (2011) divided the elevation process into 12 typical activities for Louisiana: push piling; raise, shore and align; footings; piers; wood stair; sanitary sewer; water; electrical; driveway and sidewalk pavement; platform for air conditioning (AC); remove/replace AC; and insulation below floor framing (per and beam only). Three additional activities are not typical for Louisiana: exterior wall; masonry stair; gas. The average cost/unit area/unit elevation for these three additional activities according to Gair et al. (2011) are 65.6 (1.9), 43.3 (1.2), and 9.0 (0.3), \$ m^{-2} m^{-1} (\$ ft^{-2} ft^{-1}), respectively.

Cost Adjustment

Cost information from the literature was normalized to represent 2015 dollars using the Engineering News-Record (ENR) average annual building cost index (i.e., average index, AI; (Grogan, 2016), which is commonly used by researchers in the construction industry (e.g., Popescu et al., 2003; Touran and Lopez 2006; Mikhed and Zemčík 2009). AI values have been determined considering nationwide changes (i.e., 20 cities) in labor rates, productivity, material prices, and the competitive condition of the building marketplace. The AI values (Grogan, 2016) are used to calculate project cost in terms of 2015 dollars [**Eq. 6**], where C_{2015} is cost in 2015, AI_{2015} is the average index of the construction cost in 2015, AI_i is the average index at time i, and C_i represents cost at time i (i.e., either project contract date or year of previous study),. Historical AI values used for 1993, 1998, 2005, and 2015 are 2,996, 3,391, 4,205, and 5,517, respectively.

$$C_{2015} = \frac{AI_{2015}}{AI_{\mathrm{i}}} \times C_{\mathrm{i}} \tag{6}$$

National average project costs (C_{NA}) were adjusted to represent Louisiana costs (C_{LA}) using average location factor, P_l [**Eq. 7**], determined by averaging all Louisiana city RSMeans location factors (RSMeans, 2015). These factors ranged between 77.8 and 87.5%, with an average of 82.6%. Summarized costs are provided along with the results of this paper in **Table 1**

$$C_{LA} = P_l \times C_{NA} \tag{7}$$

Louisiana Elevation Project Data

Data were collected from scanned GOHSEP documents, corresponding to single-family homes elevated after major hurricane and flood events from 15 parishes (counties) in southern Louisiana between 2005 and 2015. Of the 805 total building records evaluated, the 666 with missing or spurious data were discarded from further analysis, thereby leaving 139 projects for statistical analysis. All cost data were adjusted to 2015 dollars, using the contract date as the original cost basis.

Seventy-one percent (71%) of the buildings had elevation certificates, from which elevation data were obtained. For the remaining buildings, FFE was obtained from other related building documents rather than the elevation certificate. The FFE in these documents was assumed to be the top of bottom floor (including basement, crawl-space, or enclosure floor) as specified in the elevation certificates.

Statistical summarization of variables used in the prediction model (**Table 2**) includes mean elevation cost per average floor area per unit ΔE (\$825/m^2/m), with a median of \$821/m^2/m, standard deviation of \$425/m^2/m, and range from \$203/m^2/m to \$2,151/m^2/m.

The correlation matrix and boxplot for each variable enhance the understanding of collected data. The correlation matrix (**Table 3**) reveals the dependence between variables before statistical analysis. Cost correlates most strongly with number of stories, followed by ΔE. The elevation project cost boxplot shows many (13 out of 139) outliers above \$500,000 (**Figure 1**). Data were weighted toward smaller values, which in turn indicates that the majority of collected data are associated with small and medium-sized homes. However, some outliers appear at the upper tail of the average floor area distribution. The ΔE boxplot shows that 67 out of 139 buildings (48%) were elevated in the range of 1.1 m (3.6 ft.) to 2.7 m (8.9ft). Data for ΔE data are slightly right-skewed but are normally distributed along the available range of elevation data.

Of the 139 elevation projects, 105 buildings are one-story, while 34 buildings are two-story. Four initial foundation types exist in the data: slab (116), crawl-space (2), pier and beam (15),

TABLE 1 | Elevation cost (cost/unit area) comparison between model 5 m and cost guidance, \$/m^2 (\$/ft^2).

	Slab foundation				Other foundation types			
ΔE	USACE	FEMA	Gair et al	Reg. Model 5 m	USACE	FEMA	Gair et al	Reg. Model 5 m
0.9 m (3 ft)	660 (61)	690 (64)	730 (68)	908 (84)	590 (55)	260 (24)	700 (65)	695 (65)
1.8 m (6 ft)	710 (66)	720 (67)	920 (86)	991 (92)	650 (60)	290 (27)	850 (79)	758 (70)
2.7 m (9 ft)	760 (71)	750 (70)	1,080 (99)	1,081 (100)	700 (65)	320 (30)	920 (85)	827 (77)

Note: USACE, FEMA, and Gair et al. costs were adjusted for Louisiana while regression costs were developed for Louisiana; all costs have been economically adjusted to represent 2015 dollars; there is no fill under any of the foundations in these estimates.

TABLE 2 | Statistical mean, median, standard deviation and range for 139 observations.

Variable	Description	Mean	Median	Standard Deviation	Range
C	Elevation cost[a]	\$241,160	\$179,567	\$172,665	[\$57,415:\$896,044]
A	Average floor area, m^2 (ft^2)	169 (1,820)	160 (1,720)	55 (590)	[54:361] [(580:3,890)]
ΔE	Delta elevation, m (ft)	1.9 (6.4)	1.9 (6.2)	0.9 (2.9)	[0.6:3.8] [(2.0:12.3)]
C/A/ΔE	Cost[a]/Unit area/Unit elevation, \$/m^2/m (\$/ft^2/ft)	830 (24)	820 (23)	430 (12)	[200:2,150] [(6:61)]

[a]*All costs have been economically adjusted to represent 2015 dollars.*

TABLE 3 | Correlation matrix for independent variables in sampled elevated homes in Louisiana, 2005–2015.

	C	*A*	*ΔE*	*S*	*F*
C	1.00*				
A	0.37*	1.00*			
ΔE	0.40*	0.05	1.00*		
S	0.71*	–0.13	0.32*	1.00*	
F	0.23*	0.16	–0.06	0.12	1.00*

Note: Asterisk in cells shows that correlation coefficient differs significantly from zero at p < *0.05.*

and piling (6). Since there were only two levels of building stories in the data set, this variable was converted to a categorical variable with levels 0 and 1, representing one- and two-story buildings, respectively. In addition, slab foundations were the most predominant foundation type, with only 23 observations of other foundation types. Thus, the foundation type variable was also converted to a categorical variable, with levels 0 and 1, representing other and slab foundations, respectively.

METHODOLOGY

Multiple Regression

Statistical model prediction depends on the type of regression model and statistical characteristics of the data, including number of variables and the data distribution for each variable (Kim et al., 2004; Sousa et al., 2007; Atici 2011). Determination of the "best" or most appropriate model depends on the model evaluation criteria. In this study, these criteria are defined as: variable significance, goodness of fit, 10-fold CV RMSE, and adherence to regression assumptions.

Variable Significance

Elevation project cost and average floor area data are non-normal and right-skewed. The elevation change data are slightly right-skewed; such skewness is reasonably expected to translate to the regression surface unless the cost values are transformed in the regression model to satisfy the assumption of normally distributed residuals. Therefore, the dependent cost variable and independent average floor area variable were transformed by a log-transformation, which is supported by other recent studies in construction cost prediction (e.g., Lowe et al., 2006; Jafarzadeh et al., 2015).

Ten statistical regression models were tested to find the best predictive model for determination of the estimated cost of elevation ($\widehat{C}$) [**Eqs. 8–17**], where $\widehat{\beta}_0$ is the estimated intercept, $\widehat{\beta}_i$ represents the estimated coefficient of regressor variable *i*, *A* is the average floor area (m^2), ΔE is elevation change (m), *S* represents the categorical number of stories variable, and *F* represents the categorical foundation type variable.

Model 1.

$$\widehat{C} = \widehat{\beta}_0 + \widehat{\beta}_1 A + \widehat{\beta}_2 \Delta E \tag{8}$$

Model 2.

$$\widehat{C} = \widehat{\beta}_0 + \widehat{\beta}_1 A + \widehat{\beta}_2 \Delta E + \widehat{\beta}_3 S + \widehat{\beta}_4 F \tag{9}$$

Model 3.

$$\widehat{C} = \widehat{\beta}_0 + \widehat{\beta}_1 \ln(A) + \widehat{\beta}_2 \Delta E + \widehat{\beta}_3 S + \widehat{\beta}_4 F \tag{10}$$

Model 4.

$$\ln\left(\widehat{C}\right) = \widehat{\beta}_0 + \widehat{\beta}_1 A + \widehat{\beta}_2 \Delta E + \widehat{\beta}_3 S + \widehat{\beta}_4 F \tag{11}$$

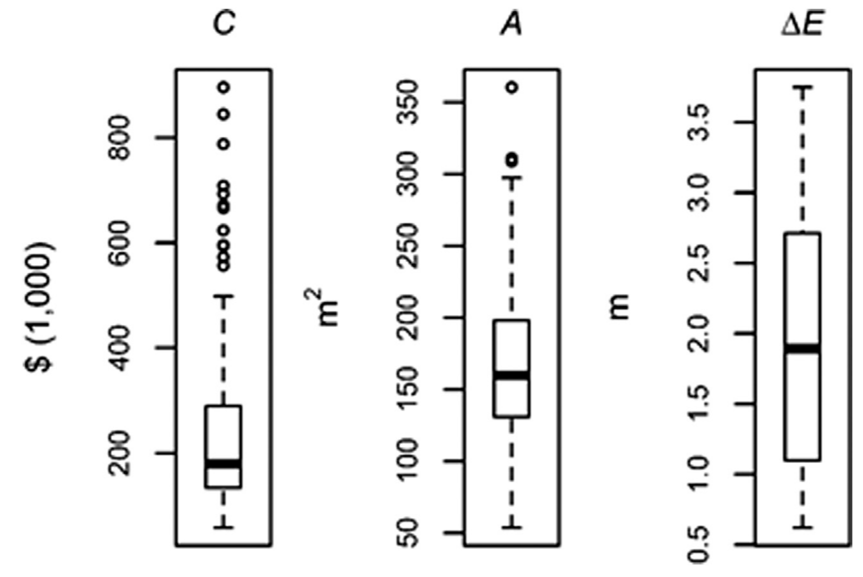

FIGURE 1 | Boxplots of continuous variables for elevated homes in Louisiana, 2005–2015, cost normalized to 2015 dollars.

Model 5.

$$\ln\left(\widehat{C}\right) = \widehat{\beta}_0 + \widehat{\beta}_1 \ln(A) + \widehat{\beta}_2 \Delta E + \widehat{\beta}_3 S + \widehat{\beta}_4 F \quad (12)$$

Model 6.

$$\widehat{C} = \widehat{\beta}_0 + \widehat{\beta}_1 A + \widehat{\beta}_2 \Delta E + \widehat{\beta}_3 (A \times \Delta E) \quad (13)$$

Model 7.

$$\widehat{C} = \widehat{\beta}_0 + \widehat{\beta}_1 A + \widehat{\beta}_2 \Delta E + \widehat{\beta}_3 (A \times \Delta E) + \widehat{\beta}_4 S + \widehat{\beta}_5 F \quad (14)$$

Model 8.

$$\widehat{C} = \widehat{\beta}_0 + \widehat{\beta}_1 \ln(A) + \widehat{\beta}_2 \Delta E + \widehat{\beta}_3 ln(A \times \Delta E) + \widehat{\beta}_4 S + \widehat{\beta}_5 F \quad (15)$$

Model 9.

$$\ln\left(\widehat{C}\right) = \widehat{\beta}_0 + \widehat{\beta}_1 A + \widehat{\beta}_2 \Delta E + \widehat{\beta}_3 (A \times \Delta E) + \widehat{\beta}_4 S + \widehat{\beta}_5 F \quad (16)$$

Model 10.

$$\ln\left(\widehat{C}\right) = \widehat{\beta}_0 + \widehat{\beta}_1 \ln(A) + \widehat{\beta}_2 \Delta E + \widehat{\beta}_3 ln(A \times \Delta E) + \widehat{\beta}_4 S + \widehat{\beta}_5 F \quad (17)$$

Model 1 was fit only with continuous variables, and Model 2 expands Model 1 with the addition of both S and F. Model 3 is the same as Model 2, but with logarithmic transformation of the continuous independent variable A, while Model 4 is the same as Model 2 but with logarithmic transformation of the response variable, also known as an exponential model. Model 5, known as a log-semi-log model, is the same as Model 3 with logarithmic transformation of the response variable and A. Models 6 through 10 are the same as the first five models, with the addition of a term representing the interaction between A and ΔE, which is transformed logarithmically in Models 8 and 10. Coefficient estimates, standard errors, and p-values were determined using R (www.r-project.org) for each of the ten models.

Regression Assumptions

For multiple linear regression, three main assumptions were tested: homoscedasticity, multicollinearity, and normality of the residuals. Homoscedasticity was tested through the Breusch-Pagan test (Breusch and Pagan 1979), with multicollinearity tested using the variance inflation factor (VIF). In models that consider interaction, multicollinearity always exists, and the VIF was not evaluated. Normality was tested using the Shapiro-Wilk test (Shapiro and Wilk 1965). Violation of the normality assumption decreases the robustness of regression results when the sample size was not large enough (Lumley et al., 2002). In some cases the violation of regression assumptions can be resolved by nonlinear transformations of regression variables (Montgomery et al., 2015) and by trimming problematic observation outliers (Andersen, 2008).

Before removing model outliers, each problematic observation was evaluated for any distinguishing features, leverage, r-student residual, and Cook's distance. An outlier with a large leverage value is an influential point because it can change the regression results. Cook's distance is another statistical measure that measures the influence of each observation in the model.

The coefficient of determination (R^2) is a statistical parameter that indicates goodness of fit between predicted and observed values; however, to compare the goodness of fit for multiple models that consider non-equal numbers of independent variables, the R^2 can be misleading because the value increases as the number of regressor variables increase. Therefore, to better represent goodness of fit for model comparison, the adjusted R^2 (R^2_{adj}) was calculated.

10-Fold Cross-Validation Root Mean Square Error

The RMSE was used to measure the error rate of prediction models. In order to obtain the RMSE, a prediction model was constructed on training data and was then used to predict data for the test set. The *RMSE* was obtained by examining the test set data on a training set fitted model [**Eq. 18**], where n is the number of observations for prediction of the test set data, $\widehat{Y}_t$ is the predicted value of observation t in the test set data, and Y_t is the actual value of observation t in the test set data.

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(\widehat{Y}_t - Y_t\right)^2} \quad (18)$$

Sometimes RMSE values resulting from only one training and one test set become sensitive to the selection of data for each set. Therefore, obtaining RMSE with K-fold CV ($K > 2$) is preferable (Zhang et al., 2011). Based on the recommendation of Kohavi (1995), this paper uses 10-fold CV for multiple regression to select the best prediction model. In each fold, the prediction error $RMSE_i$ was calculated, and the mean of all prediction errors (E) is the 10-fold CV RMSE for the prediction model (Priddy and Keller, 2005), where $RMSE_i$ is the RMSE for fold i [**Eq. 19**].

$$E = \frac{1}{10}\sum_{i=1}^{10} RMSE_i \quad (19)$$

Random Forest

Random forest (Breiman, 2001) is a robust data mining model used for both prediction (i.e., regression) and classification. This ensemble method was constructed based on the equal averaging of many random trees in the classification and regression tree (CART) method (Breiman, 2001) to obtain a model with reduced variance. In the random forest, every tree was created by a bootstrap sample from the training data, and the tree grows to a maximum depth without pruning (Breiman, 2001; Cutler et al., 2007). The random forest algorithm selects regressor variables randomly at each node. Additionally, the random forest is useful for ranking regressor variables by their importance in prediction. The "randomForest" package in the R program was used for random forest analysis in this study.

Generalized Additive Model

The GAM is used to identify the relationship between input and output variables in nonlinear models. It relaxes the strictly linear relationship between the response and the regressors, allowing regressors to have a general and flexible relationship to the response, but maintains additive or non-interactive structure (Moore et al., 2011; Shimizu et al., 2014; Larsen, 2015; Taghinezhad et al., 2020b). Although we do not consider it here, GAMs can additionally accommodate non-normal responses with added flexibility through a nonlinear link function (Xiang, 2001; Han et al., 2009; Calabrese and Osmetti, 2015). This study used the "gam" package (Hastie, 2020) in the R program to fit the GAM. The smoothing function of spline fit on continuous variables of A and ΔE is applied to the model. To obtain the optimum fit with the lowest RMSE, the models are varied based on applying the logarithmic transformation on C and A variables and also changing the degrees of freedom in spline fit smoothing functions (i.e., 4, 2, and 1) because changing degree of freedom tunes the flexibility in the regressors, and is thus explored as a hyperparameter. In GAM Models 11–15, g represents the identity link with normal response, $\widehat{s}$ represents the smoothing function of spline fit, and df represents the degree of freedom.

TABLE 4 | Parameter estimate, standard error, and *p*-value for multiple regression models.

Model #	Coefficient	Parameter	Estimate	Std. Error	*p*-value
1	$\widehat{\beta}_0$	*Intercept*	−92,079	48,266	0.058
	$\widehat{\beta}_1$	*A*	1,110	230	<0.001 *
	$\widehat{\beta}_2$	Δ*E*	75,292	14,296	<0.001*
2	$\widehat{\beta}_0$	*Intercept*	−155,123	32,080	<0.001*
	$\widehat{\beta}_1$	*A*	1,397	141	<0.001*
	$\widehat{\beta}_2$	Δ*E*	30,492	9,078	0.001*
	$\widehat{\beta}_3$	*S*	284,495	18,765	<0.001*
	$\widehat{\beta}_4$	*F*	38,510	20,613	0.064
3	$\widehat{\beta}_0$	*Intercept*	−110,7306	114,089	<0.001*
	$\widehat{\beta}_1$	ln(*A*)	233,401	22,712	<0.001*
	$\widehat{\beta}_2$	Δ*E*	34,503	8,898	<0.001*
	$\widehat{\beta}_3$	*S*	282,077	18,420	<0.001*
	$\widehat{\beta}_4$	*F*	33,822	20,366	0.099
4	$\widehat{\beta}_0$	*Intercept*	1.056E+01	9.470E-02	<0.001*
	$\widehat{\beta}_1$	*A*	5.862E-03	4.161E-04	<0.001*
	$\widehat{\beta}_2$	Δ*E*	1.003E-01	2.680E-02	<0.001*
	$\widehat{\beta}_3$	*S*	9.474E-01	5.539E-02	<0.001*
	$\widehat{\beta}_4$	*F*	2.643E-01	6.085E-02	<0.001*
5	$\widehat{\beta}_0$	*Intercept*	6.641	0.340	<0.001*
	$\widehat{\beta}_1$	ln(*A*)	0.964	0.068	<0.001*
	$\widehat{\beta}_2$	Δ*E*	0.118	0.026	<0.001*
	$\widehat{\beta}_3$	*S*	0.935	0.055	<0.001*
	$\widehat{\beta}_4$	*F*	0.247	0.061	<0.001*
6	$\widehat{\beta}_0$	*Intercept*	−52,487	109,178	0.631
	$\widehat{\beta}_1$	*A*	877	621	0.160
	$\widehat{\beta}_2$	Δ*E*	56,872	47,733	0.236
	$\widehat{\beta}_3$	(*A* × Δ*E*)	108	266	0.686
7	$\widehat{\beta}_0$	*Intercept*	−45,595	69,118	0.511
	$\widehat{\beta}_1$	*A*	791	367	0.033*
	$\widehat{\beta}_2$	Δ*E*	−19,244	29,281	0.512
	$\widehat{\beta}_3$	(*A* × Δ*E*)	286	160	0.077
	$\widehat{\beta}_4$	*S*	288,621	18,757	<0.001*
	$\widehat{\beta}_5$	*F*	31,394	20,832	0.134
8	$\widehat{\beta}_0$	*Intercept*	−1,123,570	119,220	<0.001*
	$\widehat{\beta}_1$	*ln*(*A*)	271,491	81,704	0.001*
	$\widehat{\beta}_2$	Δ*E*	55,847	44,864	0.215
	$\widehat{\beta}_3$	ln(*A* × Δ*E*)	−38,662	79,641	0.628
	$\widehat{\beta}_4$	*S*	282,645	18,510	<0.001*
	$\widehat{\beta}_5$	*F*	32,388	20,637	0.119
9	$\widehat{\beta}_0$	Intercept	1.051E+01	2.064E-01	<0.001*
	$\widehat{\beta}_1$	*A*	6.172E-03	1.096E-03	<0.001*
	$\widehat{\beta}_2$	Δ*E*	1.257E-01	8.744E-02	0.153
	$\widehat{\beta}_3$	(*A* × Δ*E*)	−1.459E-04	4.777E-04	0.760
	$\widehat{\beta}_4$	*S*	9.453E-01	5.601E-02	<0.001*
	$\widehat{\beta}_5$	*F*	2.680E-01	6.221E-02	<0.001*
10	$\widehat{\beta}_0$	*Intercept*	6.638	0.355	<0.001*
	$\widehat{\beta}_1$	ln(*A*)	0.970	0.243	<0.001*
	$\widehat{\beta}_2$	Δ*E*	0.121	0.134	0.368
	$\widehat{\beta}_3$	ln(*A* × Δ*E*)	−0.005	0.237	0.982
	$\widehat{\beta}_4$	*S*	0.935	0.055	<0.001*
	$\widehat{\beta}_5$	*F*	0.247	0.061	<0.001*

TABLE 5 | Model evaluation results for multiple regression models.

Model #	Homosceda-sticity	Multicollin-earity	Normality	R^2	Adjusted R^2	10-Fold CV RMSE
1	F	*p*	F	0.28	0.27	133,324
2	F	*p*	F	0.75	0.74	86,447
3	F	*p*	F	0.76	0.75	85,436
4	*p*	*p*	*p*	0.82	0.81	70,393
5	F	*p*	F	0.82	0.81	63,618
6	F	NA	F	0.28	0.27	134,127
7	F	NA	F	0.76	0.75	86,138
8	F	NA	F	0.76	0.75	87,216
9	*p*	NA	*p*	0.82	0.81	71,070
10	F	NA	F	0.82	0.82	64,127

Note: p = *pass, F = fail, NA = not applicable.*

Model 11.

$$g(\widehat{C}) = \widehat{\beta}_0 + \widehat{s}(A, df = 4) + \widehat{s}(\Delta E, df = 4) + \widehat{\beta}_1 S + \widehat{\beta}_2 F \tag{20}$$

Model 12.

$$g[ln(\widehat{C})] = \widehat{\beta}_0 + \widehat{s}(ln(A), df = 4) + \widehat{s}(\Delta E, df = 4) + \widehat{\beta}_1 S + \widehat{\beta}_2 F \tag{21}$$

Model 13.

$$g[ln(\widehat{C})] = \widehat{\beta}_0 + \widehat{s}(ln(A), df = 2) + \widehat{s}(\Delta E, df = 2) + \widehat{\beta}_1 S + \widehat{\beta}_2 F \tag{22}$$

Model 14.

$$g[ln(\widehat{C})] = \widehat{\beta}_0 + \widehat{s}(ln(A), df = 2) + \widehat{\beta}_1 \Delta E + \widehat{\beta}_2 S + \widehat{\beta}_3 F \tag{23}$$

Model 15.

$$g[ln(\widehat{C})] = \widehat{\beta}_0 + \widehat{\beta}_1 ln(A) + \widehat{s}(\Delta E, df = 2) + \widehat{\beta}_2 S + \widehat{\beta}_3 F \tag{24}$$

Model 11 is the GAM with four degrees of freedom on smoothing functions, Model 12 includes a logarithmic transformation of the response variable and A with inclusion of smoothing function on the continuous variables of A and ΔE. Model 13 is the same as Model 12 but with two degrees of freedom on smoothing functions. Finally, Models 14 and 15 are the same as Model 13 but with smoothing function on only A or ΔE, respectively. It must be noted that the response variable in all the GAMs have identity link function with normal response.

RESULTS

Multiple Regression

The parameter estimate, standard error, and significance p-value of each variable for all ten models are shown in **Table 4**. The results indicate that the p-values of all selected variables in Models 1, 2, 3, and 6 are less than the significance level of 0.05, indicating that all variables in these four models have significant impacts on the dependent cost variable. The standard error shows the variability of each parameter estimate applicable to the regression model. Of these, only Models 4 and 5 show significance of all independent variables with low standard errors.

The criteria for selecting the best among the ten proposed models are the fulfillment of the statistical regression assumptions, p-value significance for all independent variables, adjusted R^2, and minimization of 10-fold CV RMSE. According to **Table 5** the only models passing the main assumptions of multiple linear regression are the exponential models (i.e., Models 4 and 9 with log transformation of dependent variable C).

Although Model 4 appears to be the preferred model for the first three criteria, Model 5 has a lower 10-fold CV RMSE with equal adjusted R^2. However, regression assumptions of normality and homoscedasticity of residuals were not satisfied. In the residual plots of normal Q-Q, scale location, and residuals vs. leverage (**Figure 2**), observations numbered 77, 100, and 101 were detected as problematic observations (2% of total).

Examination of the corresponding buildings for these observations revealed that they are extraordinary projects with an unusual A or E (**Table 6**). For instance, observation #77 has a very low building cost while the building area is large. Therefore, in Model 5m, these three observations were excluded from Model 5, which then satisfied the regression assumptions (**Figure 3**).

Table 7 provides the estimated coefficients, standard errors, and p-values for the Model 5 mm parameters. The p-values are significant for all parameters in the model and the high R^2 and adjusted R^2 values of 0.86 and 0.85, respectively, indicate a good fit between data and model. Additionally, the 10-fold CV RMSE is decreased and changed to 61,542. The results for the Model 5 m reveal no violation of tested assumptions (i.e., the p-value of the Shapiro-Wilk test for the normality assumption is 0.063, the p-value of the Breusch-Pagan test for the homoscedasticity assumption is 0.559, and the VIF results for all regressor variables are less than the threshold of 10 [$VIF_A = 1.06$, $VIF_{\Delta E} = 1.14$, $VIF_S = 1.18$, $VIF_F = 1.04$]).

Random Forest and Generalized Additive Model

The random forest model out-of-bag (OOB) error decreased dramatically with the first 50 trees, after which the test-error becomes nearly constant (**Figure 4**). Therefore, random forest is applied with 800 trees to obtain the best results. The random forest variable importance option indicates that S, A, ΔE, and F are the most important variables in the random forest model, in order.

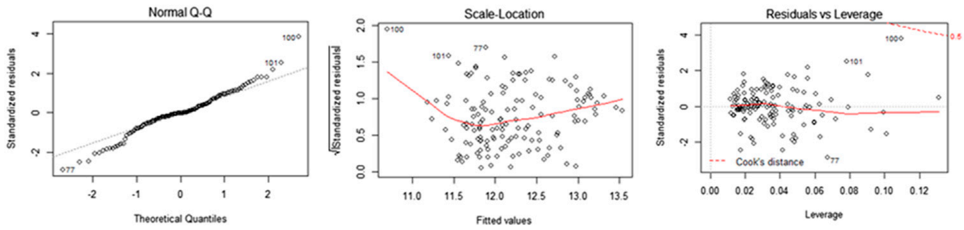

FIGURE 2 | Model 5 residuals plots of normal Q-Q, scale location, and residuals vs. leverage.

TABLE 6 | Outlier observations in model 5 with the description of the issue.

N	C	A	E	S	F	Issue	Leverage	R-student	Cooks D
77	$71,051	206	0.9	0	0	Low cost; big size	0.07	−2.97	0.12
100	$111,767	54	1.9	0	0	Very small size	0.11	4.03	0.36
101	$172,775	99	3.4	0	0	Very high elevation	0.08	2.56	0.11

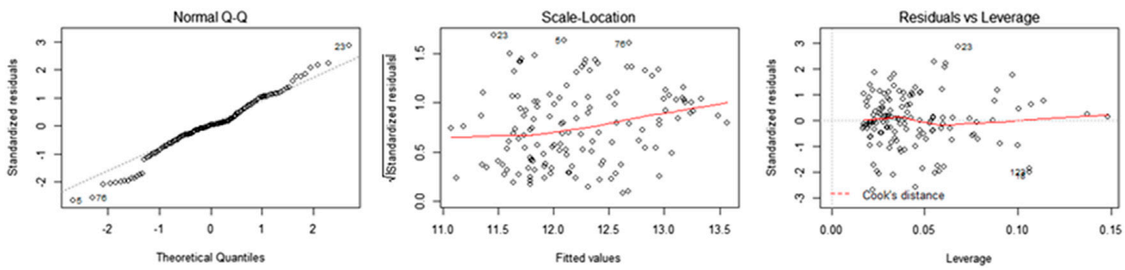

FIGURE 3 | Model 5 m residuals plots of normal Q-Q, scale location, and residuals vs. leverage (Model 5 after deleting observations 77, 100, and 101).

TABLE 7 | Parameter estimate, standard error, and *p*-value for multiple regression model 5 m.

Coefficient	Parameter	Estimate	Std. Error	*p*-value
$\hat{\beta}_0$	*Intercept*	6.062 (3.495)	0.319 (0.467)	<0.001 *
$\hat{\beta}_1$	ln(*A*)	1.080	0.063	<0.001 *
$\hat{\beta}_2$	*ΔE*	0.096 (0.029)	0.024 (0.007)	<0.001 *
$\hat{\beta}_3$	*S*	0.969	0.049	<0.001 *
$\hat{\beta}_4$	*F*	0.268	0.057	<0.001 *

Note: The values in parentheses reflect U.S. units.

The 10-fold CV RMSE for the random forest model is 72,843, which is greater than the best regression model. The RMSEs for five GAMs on Models 11–15 are: 89,728, 68,080, 65,182, 64,641, and 64,200, respectively. The results show that Model 15 with logarithmic transformation of response and *A* variables and spline smoothing on *ΔE* variable with two degrees of freedom has the best RMSE among all the other GAMs. The partial residual plots of this model show the nonlinear effect of regressors ln(*A*) and *ΔE* (**Figure 5**). We find that *ΔE* is essentially linear in nature, whereas the ln(*A*) effect requires mild flexibility.

The 10-fold CV RMSEs in the statistical cost estimation models show that the regression Model 5 m (10-fold CV RMSE = 61,542) has the best prediction capability. Therefore, this model is selected to use in this research to compare with the elevation costs on the literature. The cost predictions by this model are shown in Appendix Table A1. **Figure 6** shows the

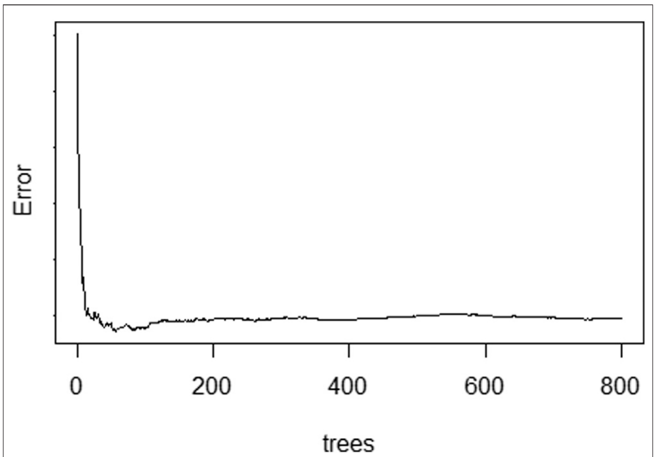

FIGURE 4 | Random forest OOB error based on the number of trees.

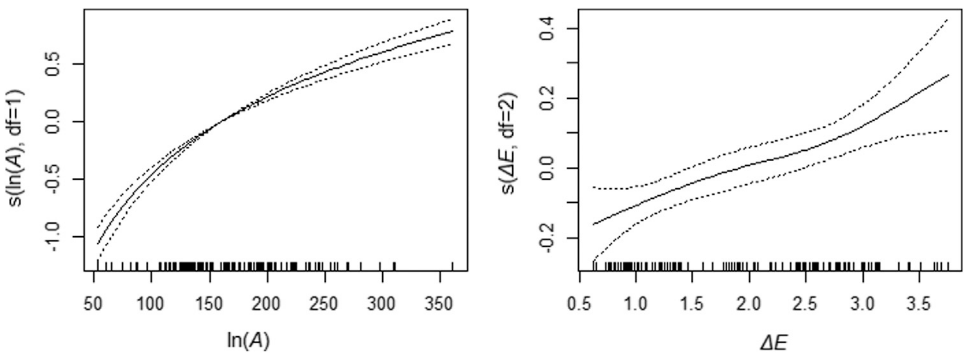

FIGURE 5 | Model 15 partial residual plots.

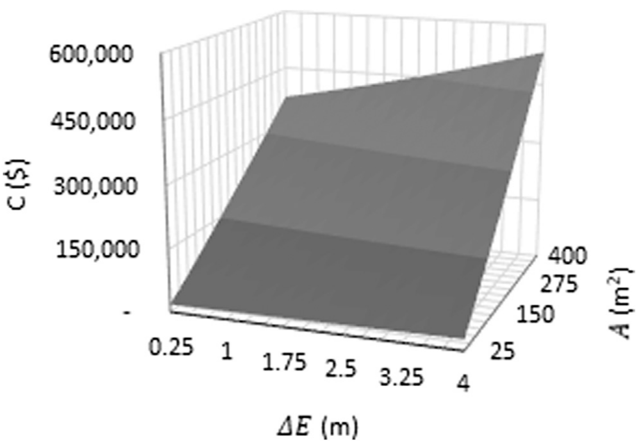

FIGURE 6 | Three-dimensional plot of the Model 5 m prediction based on *A* and *ΔE* for one-story homes with slab foundations.

predicted project cost calculated using the Model 5 m based on *A* and *ΔE* for homes with one-story and slab foundation. The other choices of *S* and *F* have exactly the same surface, but shifted vertically. The additive structure, and that perhaps GAMs, although having similar structure (see partial residual plots), are overfitting the smooth relationship and thus mildly suffers with external prediction.Comparison With Cost Literature

In this section, the regression Model 5 m predictions are compared with the USACE (1993), FEMA (1998), and Gair et al (2011) estimates previously described. As a fair basis for comparison, all estimates are adapted to 2015 dollars using **Eq. 6** and Louisiana location using **Eq. 7**. In both Gair et al. (2011) and USACE (1993), the general contractor's charge for overhead and profit is considered to be 10% of the estimated final costs according to the recommendations by these two guidelines. Additionally, Gair et al (2011) estimates include a 5.9% charge for insurance and a 20% contingency factor due to the uncertainty and any unpredicted issue that may happen during the construction work. According to instructions for USACE (1993) estimates, the professional engineering design and landscaping costs must be added to original represented costs in USACE (1993) for elevation.

Table 1 shows the elevation cost based on USACE (1993), FEMA (1998), and Gair et al (2011) cost guidance and regression prediction for one-story buildings in six specific case studies. In all examined case studies, elevation of buildings with existing slab foundations is more expensive than elevation of buildings with other foundation types.

Figure 7 demonstrates graphically the difference between the predicted elevation cost using regression models and cost guidance estimates. The results indicate that USACE (1993) and FEMA (1998) estimates are lower than those in Gair et al. (2011) and regression approaches employed here.

DISCUSSION

The statistical prediction model is based on the generalization from real and completed elevation projects; therefore, it gives a more realistic estimation with actual cost varieties in the market. Additionally, because a wide range of buildings with different conditions was used in the statistical prediction model, it is able to predict cost based on simple achievable building attributes. The elevation cost comparison in **Table 1** and **Figure 7** shows that elevating other foundation types is considerably less expensive than elevating slab foundations. Also, for slab foundation elevation, USACE and FEMA guidance underpredict Louisiana elevation costs; for other foundations, FEMA continues to underpredict, but USACE is closer to Louisiana costs.

The partial plot of the selected GAM model shows that cost has a nonlinear relationship with building average floor area. Therefore, the previous cost guidance (USACE, 1993; FEMA, 1998; Gair et al., 2011) that estimates elevation cost only with a single building size, and then generalizes the cost based on that case study, biases results in buildings with different average floor area. Furthermore, the random forest model shows that the number of stories is the most important variable in prediction of elevation project cost, but this variable is not included in current elevation cost guidance.

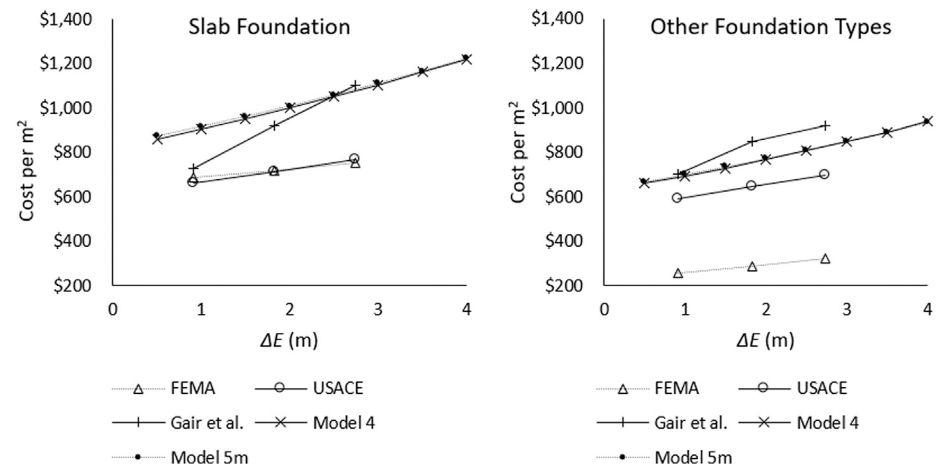

FIGURE 7 | Average cost/m^2 to elevate a one-story home with slab foundation **(left)** and other foundation types **(right)**.

However, none of the three above-mentioned guidelines have evaluated the effect of important variables such as the building average floor area and number of stories. The USACE (1993) and FEMA (1998) estimates are lower than the newer estimates by Gair et al (2011) and statistical prediction models. The differences may come from changing the construction techniques and equipment over time, and the inherent error in cost adjustment over time. This result suggests that the USACE (1993) and FEMA (1998) guidelines do not have advantages over the newer estimates by Gair et al. (2011) and the statistical prediction models described here. The Gair et al. (2011) study is more conservative than other cost guidance because it considers the 25% contingency factor for any unpredictable construction activities.

Among the tested regression models, Model 5 has the best external prediction ability, with all significant coefficient variables, higher adjusted R^2, and lower 10-fold CV RMSE. But unlike Model 4, which satisfies all regression assumptions, the normality and homoscedasticity assumptions may be violated based on the *p*-values of these tests, which fall below the significance level of 0.05. Therefore, this study suggests using the modified Model 5 (i.e., Model 5 m) with trimmed outliers, because it passes all regression assumptions. However, the trimmed otliers did not considerably change the trendline of Model 5 as the plots of Models 5 and 5 m are nearly identical (**Figure 6**). The random forest and GAM prediction accuracy are inferior to that of regression Models 5 and 5 m. Accordingly, the regression Model 5 m has a better prediction ability for C among all the models and is selected for use in this study. Also, the regression models are preferable to random forest and GAM in ease of interperation and prediction of the results because the equation and estimated coeffficents can be used easily to estimate the dependent variable without using sophisticated computer programs.

The cost as calculated in statistical predictions can change based on variables that do not exist in the current guidelines. However, regression Model 5 m shows a substantial agreement between its predictions and the guidelines. For instance, there is a difference of between 0.1 and 24.4% in the Model 5 m estimates vs. Gair et al. (2011) case studies. Therefore, the results suggest that project cost prediction with regression Model 5 m enhances future BCA for flood-mitigated properties.

CONCLUSION AND SUMMARY

To provide a series of building elevation project cost case studies based on cost guidance, this study adjusted the costs in the available guidance to represent those in year 2015 for a Louisiana location. According to the cost guidance results for single-family homes with three levels of elevation and three disparate cost analyzing methods, the occupancy phase elevation cost with USACE estimation is between \$590/m^2 (\$55/ft^2) and \$760/m^2 (\$71/ft^2), with FEMA estimation falling between \$260/m^2 (\$24/ft^2) and \$750/m^2 (\$70/ft^2), and the Gair et al. (2011) method suggesting between \$700/m^2 (\$65/ft^2) and \$1,100/m^2 (\$99/ft^2).

To find an appropriate statistical prediction model, ten regression models along with one random forest model and five GAMs were studied for cost modeling. The correlation matrix prior to regression analysis shows the existence of correlation between cost and all independent variables. However, according to the random forest variable importance function, elevation cost is most strongly affected by the number of stories – an attribute that has been neglected in previous elevation cost guidance – and change in elevation.

The regression 10-fold CV RMSE results suggest that a log-semi-log model without an interaction term and with trimmed outliers (i.e., Model 5 m) has the lowest RMSE among the tested regression models. In addition, this model makes all independent variables significant with no violation of statistical assumptions and high goodness of fit with R^2 of 0.85. Therefore, the results suggest that regression models can be used successfully in project cost prediction for elevation projects to address the cost issue in BCA and to overcome barriers in existing cost guidance methods.

The regression study shows that for projects undertaken in Louisiana with adjusted costs to 2015 dollars, the elevation costs for slab foundations are \$908/m^2 (\$84/ft^2) to elevate 3 ft, \$991/m^2 (\$92/ft^2) to elevate 6ft, and \$1,081/m^2 (\$100/ft^2) to elevate 9ft. The elevation costs for other foundation types are \$695/m^2 (\$65/ft^2) to elevate 3ft, \$758/m^2 (\$70/ft^2) to elevate 6ft, and \$827/m^2 (\$77/ft^2) to elevate 9ft.

In recent decades new data collection technologies make data more available for analysis in machine learning prediction models.

The results suggest that statistical data prediction models in this study can be used successfully in cost estimation for construction projects, especially for estimation of project costs in natural hazard mitigation projects. However, the statistical modeling of cost in this study suggests that proper model selection is important for improving model prediction. For instance, the RMSE in regression modeling can be improved substantially by choosing proper independent variables and transformation on regression variables specifically when the variables are not distributed normally. The random forest error is decreased by selection of the proper number of trees and the RMSE in GAM analysis can be improved by transformation of variables, applying the smoothing functions on proper variables, and changing the degrees of freedom for smoothing functions.

In future studies, the same methodology can be used for prediction of elevation cost for new buildings during the construction phase. Such information would be useful for adjusting economically the elevation mitigation benefits for new buildings and comparing that estimate with elevation cost in the occupancy phase. Additionally, by knowing the additional cost of elevation in new construction, builders could offer the choice of freeboard (elevation higher than BFE) to the owners as an option for construction in floodprone areas. Also in future studies, the mitigation cost can be predicted by statistical methods for other types of mitigation projects, such as hurricane and tornado wind mitigations.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the Louisiana Governor's Office of Homeland Security and Emergency Preparedness. Restrictions apply to the availability of these data, which were used under license for this study.

AUTHOR CONTRIBUTIONS

AT and CF contributed conception and design of the study; JG provided data; AT and CF organized the database; AT performed the statistical analysis; BM helped with statistical analysis; IN provided instructions to improve the paper quality; AT wrote the first draft of the manuscript; and RR wrote sections of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX A. ELEVATION PROJECT COST ESTIMATES

Table A1 | Elevation project cost estimates by the selected regression model (Model 5 m).

One-story; slab foundation

A (m^2)	ΔE (m) 0.5	1	1.5	2	2.5	3	3.5	4
50	$40,255	$42,234	$44,311	$46,490	$48,776	$51,174	$53,690	$56,330
100	$85,100	$89,285	$93,675	$98,281	$103,113	$108,183	$113,503	$119,084
150	$131,859	$138,342	$145,145	$152,282	$159,769	$167,625	$175,867	$184,515
200	$179,905	$188,751	$198,032	$207,769	$217,985	$228,704	$239,949	$251,748
250	$228,931	$240,188	$251,998	$264,389	$277,389	$291,029	$305,339	$320,353
300	$278,754	$292,461	$306,841	$321,929	$337,758	$354,366	$371,790	$390,071
350	$329,248	$345,438	$362,423	$380,244	$398,941	$418,557	$439,137	$460,730
400	$380,325	$399,026	$418,646	$439,231	$460,829	$483,488	$507,261	$532,204

Two-story; slab foundation

A (m^2)	ΔE (m) 0.5	1	1.5	2	2.5	3	3.5	4
50	$106,084	$111,300	$116,773	$122,515	$128,539	$134,859	$141,490	$148,447
100	*$224,265*	$235,292	$246,862	$259,000	$271,735	$285,097	$299,115	$313,823
150	$347,488	$364,574	$382,501	$401,309	$421,041	$441,744	$463,465	$486,254
200	$474,104	$497,416	$521,875	$547,536	$574,458	$602,705	$632,340	$663,433
250	$603,305	$632,970	$664,093	$696,747	$731,007	$766,951	$804,662	$844,228
300	$734,603	$770,724	$808,621	$848,381	$890,096	$933,863	$979,782	$1,027,958
350	$867,671	$910,335	$955,097	$1,002,059	$1,051,331	$1,103,026	$1,157,262	$1,214,166
400	$1,002,274	$1,051,556	$1,103,262	$1,157,510	$1,214,426	$1,274,140	$1,336,790	$1,402,521

One-story; other foundations

A (m^2)	ΔE (m) 0.5	1	1.5	2	2.5	3	3.5	4
50	$30,791	$32,305	$33,894	$35,560	$37,309	$39,143	$41,068	$43,087
100	$65,094	68$,294	$71,653	$75,176	$78,872	$82,750	$86,819	$91,088
150	$100,860	$105,819	$111,022	$116,481	$122,209	$128,218	$134,522	$141,137
200	$137,611	$144,377	$151,476	$158,924	$166,739	$174,937	$183,539	$192,564
250	$175,111	$183,722	$192,755	$202,233	$212,177	$222,610	$233,556	$245,040
300	$213,221	$223,705	$234,705	$246,246	$258,354	$271,057	$284,385	$298,369
350	$251,845	$264,228	$277,220	$290,851	$305,153	$320,157	$335,900	$352,416
400	$290,914	$305,218	$320,226	$335,972	$352,491	$369,824	$388,008	$407,087

Two-story; other foundations

A (m^2)	ΔE (m) 0.5	1	1.5	2	2.5	3	3.5	4
50	$81,144	$85,134	$89,320	$93,712	$98,320	$103,155	$108,227	$113,548
100	$171,542	$179,977	$188,826	$198,111	$207,852	$218,073	$228,795	$240,046
150	$265,796	$278,866	$292,578	$306,964	$322,058	$337,894	$354,508	$371,939
200	$362,646	$380,478	$399,186	$418,814	$439,408	$461,014	$483,682	$507,465
250	$461,473	$484,163	$507,970	$532,947	$559,153	$586,647	$615,492	$645,757
300	$561,903	$589,532	$618,520	$648,933	$680,842	$714,319	$749,443	$786,293
350	$663,688	$696,322	$730,561	$766,483	$804,171	$843,713	$885,199	$928,725
400	$766,647	$804,344	$843,894	$885,388	$928,924	$974,599	$1,022,521	$1,072,799

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Educational Theory-Integrated Construction Industry Training: State-of-the-Art Review

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Workforce training is needed throughout the construction industry to create and maintain competent workers; unfortunately, most construction training and education research focuses on university student education. Integrating education science theory into construction training has the potential to improve industry training, but the status of this integration has not been well articulated. To address this gap, this article undertakes a state-of-the-art review of education theory–integrated construction training for current industry professionals. To measure the extent of educational theory integration, this article identifies and summarizes studies that meet inclusion criteria, identifies the frequency of occurrence of Bloom's Taxonomy verbs as a measure of student learning outcomes, and identifies and compares commonly used words within the identified construction training literature and foundational educational theory literature. This article presents a systematic review of published construction workforce training studies that have incorporated educational theory in the design and implementation of the training. The results reveal that, of the 15 construction training studies that met the inclusion criteria, two-thirds (2/3) focused on worker safety and only three studies (20%) targeted managers or designers. Fewer than 35% of terms that were identified as frequently used terms in the published construction training studies were categorized as educational. The results of this study provide a baseline of education theory–integrated construction training research, from which gaps and best practices can be identified and implemented to improve construction industry training.

Keywords: workforce training, educational theories, Bloom's Taxonomy, andragogy, content analysis

INTRODUCTION

Job training plays a vital role in the creation and maintenance of a capable workforce in the construction industry (Waddoups, 2014). Training is effective when learning is promoted (Ahmad et al., 2012), which is optimized through theories developed within the field of education science (Ormrod, 2008) that focus on how learners obtain, process, and retain information. Despite the well-known shortage of construction industry training (Rahim et al., 2016; Silva et al., 2018; Akomah et al., 2020), there is a surprising lack of recommendations for holistic improvement of construction training across the industry. For example, the suggestion by Tatum (2018) that graduate programs may be a potential remedy to increase skills within the construction industry fails to address the ubiquitous lack of training (Kazaz et al., 2008) for the construction workforce.

Learning is the perpetual change in conduct generated by experience (Bass and Vaughan, 1968). Throughout human history, interest in learning has been evident, becoming amplified in the 20th century when several proven learning theories emerged (Rücker, 2017). Kaufman (2003) suggested that when learning theories are employed in teaching methods, both knowledge and skills increase. The incorporation of educational theory into workforce training has been noted in industries such as information technology (e.g., Gaikwad and Bharathi, 2018), computer science (e.g., Antonis et al., 2011), ecology (e.g., Parkinson et al., 2003), and law enforcement (e.g., Michael, 2003), to name a few. A growing body of research has focused on education of construction management and civil engineering undergraduate and graduate students (e.g., Jensen and Fischer, 2006; Harfield et al., 2007; Kamardeen, 2014; Cho et al., 2015; Lee et al., 2016; Holt et al., 2018; Talley and Torres, 2018; Poon, 2019; Torres et al., 2019; Kim and Irizarry, 2020); however, few studies have focused on construction industry workplace training (Detsimas et al., 2016). The proven outcomes associated with formalized educational theory warrant a comprehensive review of the current state of construction workforce training that integrates educational theory in its design.

To improve our understanding of the state of construction training for current construction professionals, serving as a starting point to understand how to overcome training-related challenges in the industry, this article provides a review of educational theory-integrated construction industry training and undertakes the following research questions:

- To what extent is educational theory integrated in construction training for current industry professionals? Which educational theories are most often integrated?
- Which construction training subject(s) most commonly include(s) educational theory for current industry professionals?
- To what extent does the construction training literature discuss student learning outcomes, quantified as the frequency of occurrence of Bloom's Taxonomy verbs?
- What is the distribution of Bloom's Taxonomy levels in the construction training literature?
- To what extent does frequent terminology used in the construction training literature match that of foundational education theory literature?

To answer these questions, a state-of-the-art review of education theory–integrated construction training for current industry professionals is undertaken. This review begins with identifying inclusion criteria to capture the literature that is relevant to this study and studies that meet these criteria are described through case review. Using autonomous counting, Bloom's Taxonomy verb categories are used to enumerate the occurrences of each Bloom's Taxonomy verb, sort terms found in the studies, and enumerate the occurrences of each verb to extract patterns across each of the studies. Autonomous counting was also used to determine the most frequently used terms across the identified studies and across the foundational educational theories referenced in the identified studies. Using the results of this analysis, comparisons are made between the terms found in the studies and the terms found in the foundational educational literature.

The contribution of this research is a systematic review of published construction workforce training studies that have incorporated educational theory in the design and implementation of the training. This study measures the extent of educational theory integration in construction industry training programs by analyzing completed research that has incorporated educational theory in training design. The results of this study provide a snapshot of the current state of professional construction training and are intended to serve as a starting point for improvement of future industry training. The intended audience of this article is construction education and training researchers, professionals, organizations, and groups.

MATERIALS AND METHODS

The methodology undertaken in this study includes the following steps: 1) relevant studies are identified through implementation of inclusion criteria, 2) each identified study is described through a case review, 3) the occurrence frequency of Bloom's Taxonomy verbs within each study is quantified as a measure of student learning outcomes, 4) frequently used terminology across all studies is identified and quantified, 5) frequently used terminology within foundational educational theory literature is identified and quantified, and 6) frequently used terminology found in steps 4 and 5 is compared.

Study Selection

The study undertaken in this article implements a structured literature review to collect data on education theory–integrated construction training for current industry professionals. This approach, called Preferred Items for Systematic Review Recommendations (PRISMA), was implemented by Moher et al. (2009). The objective is to understand the extent that construction training programs that have embedded established educational theory in their design or implementation of the training. The main search keywords were "construction industry," "education theory," and "training." The main research engines were Google Scholar and the Grok Knowledge Base, and they were used to identify relevant research outputs. The following inclusion criteria were established to identify recent, relevant peer-reviewed construction training studies published after 2005 for investigation in this study:

1. The training focuses on the current construction industry workforce, including construction workers (W), project managers (M), and designers (D).
2. The training incorporated educational theory in the creation or implementation of the training.

Using the keywords mentioned above, a search of literature was conducted resulting in 475 research outputs then increased to

TABLE 1 | Bloom's Taxonomy categories and associated verbs (Anderson and Krathwohl 2001).

Remember	Understand	Apply	Analyze	Evaluate	Create
Choose	Arrange	Apply	Analyze	Appraise	Arrange
Define	Cite	Chart	Calculate	Assess	Assemble
Enumerate	Classify	Collect	Categorize	Choose	Collect
Identify	Comprehend	Compute	Compare	Compare	Compose
Indicate	Describe	Construct	Contrast	Contrast	Construct
Know	Discuss	Demonstrate	Criticize	Criticize	Create
Label	Explain	Document	Debate	Critique	Design
List	Explore	Dramatize	Detect	Decide	Formulate
Match	Express	Employ	Determine	Defend	Generate
Memorize	Extrapolate	Give examples	Diagram	Estimate	Integrate
Name	Generalize	Interpret	Differentiate	Evaluate	Organize
Omit	Identify	Investigate	Disassemble	Grade	Perform
Recall	Indicate	Operate	Distinguish	Judge	Plan
Record	Infer	Practice	Examine	Justify	Prepare
Relate	Interpret	Predict	Experiment	Measure	Produce
Repeat	Judge	Schedule	Inspect	Rate	Propose
Reproduce	Locate	Shop	Inventory	Reframe	Set up
Select	Manage	Show	Justify	Revise	Synthesize
State	Match	Sketch	Question	Score	
Underline	Paraphrase	Transfer	Relate	Select	
	Recognize	Translate	Separate	Value	
	Report	Use	Solve	Weigh	
	Represent		Subdivide		
	Restate		Test		
	Review				
	Show				
	Suggest				
	Summarize				
	Tell				
	Trace				
	Translate				

483 through identification of other sources referenced in the initial search results. After removing duplicates, applying the inclusion criteria, and additional quality measures, 15 publications were selected for the review, indicating limited research conducted in this area. The selection process is illustrated in the PRISMA flow chart in **Figure 1**.

The following information was recorded from the relevant publications that met the inclusion criteria: location (i.e., country) where the study took place, educational theory employed, training subject, and the audience (W, M, and D). Adult learning or adult education was often referenced as the educational theory employed, which was recoded as "andragogy," defined as the methodology for teaching adult learners (Knowles, 1980). To identify different approaches, a summary table was constructed comparing the cases that met the inclusion criteria.

Training Case Review

The review begins by summarizing the objectives, methods, and results in a case review. The case review is created to provide context of the studies.

Bloom's Taxonomy Verb Frequency

Bloom's Taxonomy is a six-level hierarchical model that classifies cognitive objectives developed by Bloom (1956) and revised by Anderson and Krathwohl (2001). Bloom's Taxonomy categories and associated verbs used to identify and quantify training learning objectives are provided in **Table 1**.

Autonomous counting, used to generate number of occurrences that stand on their own merit (Hannah and Lautsch, 2011), was used to enumerate the occurrences of each Bloom's Taxonomy verb to extract patterns across each of the studies, a method which Horner et al. (2011) implemented to evaluate the potential effectiveness of lesson plans designed for college courses. NVivo 12, a qualitative data analysis software application, was used to identify the frequency of occurrence of each verb by level. To identify common gaps, the frequency of all verbs within each level is reported, along with the most frequent verbs within each level.

While autonomous counting is effective in generating data that produces interpretable results by analyzing the outcome of the counting methodology, potential for error in the results exists. Due to the nature of the terms that are counted, it is possible that certain terms that are not used to represent the training program are used throughout the articles that have undergone review. Due to the large quantity of text reviewed, NVivo 12 was used to accomplish this goal of counting and it is not possible for software to make these distinctions. However, occurrences of terms used that are categorized by Bloom's Taxonomy that do not represent the training program are limited and do not affect the outcome of this study. This method was used to provide a metric by which to characterize the language on a general level to determine the

TABLE 2 | Identified educational theory-integrated construction industry training studies.

Study number and reference	Country	Educational theory	Subject	Audience
(1) Akanmu et al. (2020)	United States	Digital game-based learning	Ergonomic safety	W
(2) Begum et al. (2009)	Malaysia	Ajzen's theory	Waste management	W
(3) Bena et al. (2009)	Italy	Andragogy	Safety	W
(4) Bhandari and Hallowell (2017)	United States	Andragogy	Safety and risk perception	W
(5) Bressiani and Roman (2017)	Brazil	Andragogy	Masonry Brick Laying	W
(6) Choudhry (2014)	China	Behaviorism	Safety	W
(7) Douglas-Lenders et al. (2017)	Australia	Self-efficacy	Leadership training for project managers	M
(8) Eggerth et al. (2018)	United States	Andragogy	Safety	W
(9) Evia (2011)	United States	The Kirkpatrick model	Safety	W
(10) Forst et al. (2013)	United States	Andragogy	Safety	W
(11) Goulding et al. (2012)	United Kingdom	Digital game-based learning	Offsite production	W, M, D
(12) Mehany et al. (2019)	United States	Long-term retention	Confined space training	W
(13) Lin et al. (2018)	United States	Andragogy	Safety	W
(14) Lingard et al. (2015)	Australia	Visual pedagogy	Construction health and safety	W
(15) Wall and Ahmed (2008)	Ireland	Blended learning	Project management	M

educational area of focus for construction industry training with educational theory embedment.

Training Content Analysis

Autonomous counting was used to determine the most frequently used terms across all identified studies, excluding those categorized as Bloom's Taxonomy verbs to identify common gaps. NVivo 12 was used to automatically determine frequently mentioned text or words that occur across the selected studies. These terms were segregated depending on if they were related to education, general construction terminology, or the training topical area.

Foundational Educational Theory Content Analysis

Content analysis was also performed to evaluate frequently mentioned ideas or concepts that occur across the foundational articles of the educational theories used in the identified training studies. Using NVivo 12, text or words mentioned across the foundational education theory articles were automatically selected.

Content Analysis Comparison

Frequent terminology found within the construction training studies was compared with frequent terminology found within the foundational educational theory publications to identify differences and similarities.

RESULTS

Study Selection

Fifteen studies describing education theory–integrated construction industry training met the inclusion criteria, listed in alphabetical order in **Table 2**. All studies referenced educational theories in their implementation or used educational theories as the basis of design. Digital game-based learning, Ajzen's theory, andragogy, behaviorism, self-efficacy, the Kirkpatrick model, visual pedagogy, long-term retention, and blended learning were identified as the educational theories implemented. Andragogy was the theory referenced most frequently, used in six of the 15 training studies (40%). Ten of the studies (67%) focused on safety as the main training subject. The training for three studies (20%) was intended for managers or designers, while training for 13 studies (87%) was intended for workers.

Training Case Review

This section presents a brief review for each of the 15 studies presented in **Table 2** to provide additional context to the scope of the current literature.

- Akanmu et al. (2020) implemented a virtual reality (VR) training focused on reducing construction worker ergonomic risks. Study participants were fit with wearable sensors to record worker posture while typical construction tasks were simulated. The educational theory implemented in this study was virtual reality training fueled by incorporating a game engine or gamification.
- Following training on the subject of waste management and waste disposal methods to part of the study group, Begum et al. (2009) administered a survey to Malaysian contractors to measure attitudes and behaviors toward waste management. Ajzen's theory was cited as the motivation for conducting the training, claiming that intention is the prerequisite to planned behavior.
- Bena et al. (2009) offered 4-h safety training modules for construction workers on a high-speed railway line project in Italy, consisting of one basic module and four job specific modules presented in a classroom environment.
- Bhandari and Hallowell (2017) conducted multimedia training that integrated adult learning principles to demonstrate the cause and effect of hand injuries during construction situations, focusing on injuries caused by falling objects and pinch points. The training simulated

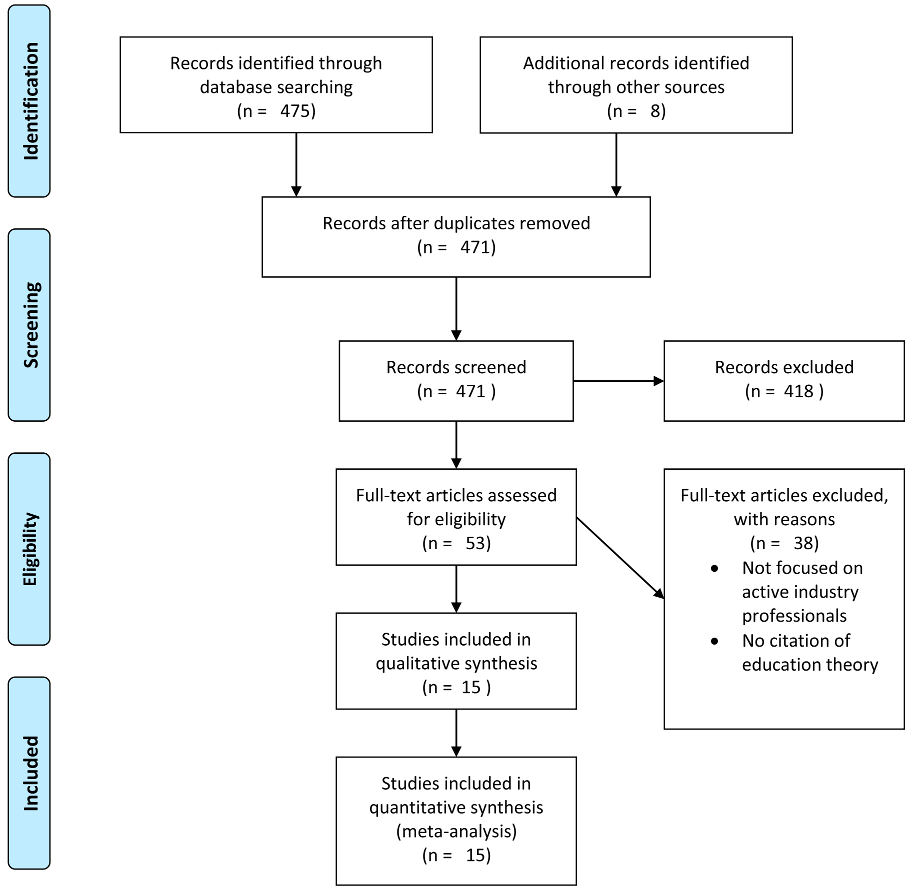

FIGURE 1 | PRISMA Flow Diagram of Studies Screened for Construction Training.

injuries that occur on jobsites with realistic prosthetic hands.

- Bressiani and Roman (2017) developed a training program for masons using andragogy. The training was provided to two groups of masons from structural masonry projects.
- Choudhry (2014) presented a safety training program for construction workers and safety observers based on behavior-based safety or behaviorism.
- Douglas-Lenders et al. (2017) presented a two-day program where participants were trained in a traditional classroom environment and through simulation to enhance leadership, communication, and safety skills.
- Eggerth et al. (2018) describe eight safety training “toolbox talks,” which are brief instructional sessions on a jobsite or in a contractor’s office. The materials were developed by adult education specialists.
- Evia (2011) describes computer-based safety training for construction workers. The Kirkpatrick model was used in the design and evaluation of the training program.
- Forst et al. (2013) describe a safety training for construction workers in seven cities across the United States. Adult learning principles were used to train worker leaders to deliver a modified version of the OSHA curriculum to their peers.
- Goulding et al. (2012) present the findings of an offsite production virtual reality training prototype where participants navigate new working conditions and unforeseen problems. This training platform was developed based on the theory of game-based training, which is linked to the theory of motivation, claiming the motivation is a key factor in effective learning.
- Mehany et al. (2019) present a confined space training program for construction workers. Tool-box talks were used as the main training delivery method for this study, where long-term retention theory was used for its design.
- Lin et al. (2018) used computer-based three-dimensional visualization, designed by adult education subject matter experts, to train construction workers on safety and fall fatalities.
- Lingard et al. (2015) implemented participatory video-based training to identify safety concerns on a construction jobsite. Workers viewed recordings of common safety concerns and shared protocols for mitigating safety risks. Visual pedagogy was used as there is evidence that a

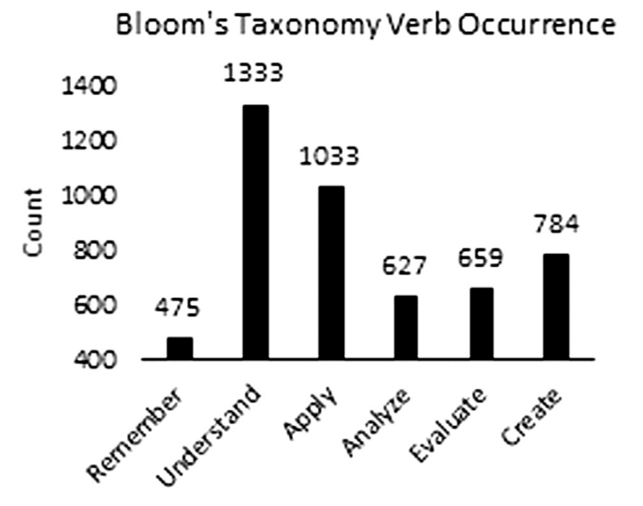

FIGURE 2 | Bloom's Taxonomy Verb Frequency by Level for Reviewed Articles (*n* = 15).

preference exists for visual rather than verbal learning (Mayer and Massa 2003).

- Wall and Ahmed (2008) explore training for project managers using construction management computerized tools. A blended learning platform was used; which refers to an educational method that combines delivery methods, including face-to-face classroom with asynchronous and/or synchronous online learning (Wu et al., 2010).

Bloom's Taxonomy Frequency

The occurrence of Bloom's Taxonomy verbs found across the fifteen studies reviewed is enumerated by the level (**Figure 2**).

Further analysis of the Bloom's Taxonomy verb categories reveals the five most frequently used verbs in each level, the frequency with which they were used, and the relative frequency of the verb usage within its respective taxonomy level. The results of this analysis are presented completely in the Appendix and summarized in **Table 3**. Note that in **Table 3**, the total percentages do not add to 100%, as other verbs were used in each level. The full results can be calculated using the data provided in the Appendix. Approximately 60–73% of the Bloom's Taxonomy verbs used in the studies are found in the five most frequently used verbs. The verb category used most frequently is "understand," accumulating more than 27% of the Bloom's Taxonomy verbs in the identified studies.

Training Content Analysis

The results of the training content analysis are presented in **Table 4**, truncated to terms appearing 40 times or more across the studies, an average of slightly more than 2.5 times article. This number was selected to capture the most important words across all the articles while ignoring inadvertently used words. The study numbers across the top of **Table 4** correspond with the order of studies in **Table 2**. Of the 23 terms with 40 or more occurrences across the 15 studies, eight were related to training or education, 13 were general to the construction industry, and two were related to safety. The terms in **Table 4** are listed alphabetically, with the number of occurrences in each study and total occurrences across the 15 studies. For purposes of this analysis, the most frequent education-related terminologies in the order of frequency (high to low) are: training, learning, behavior, study, knowledge, experience, simulation, and group. Studies 2, 4, 11, 14, and 15, each have more than 50 occurrences of these eight most common terms while studies six and eight have fewer than 20 occurrences.

TABLE 3 | Absolute and relative frequencies of most frequently used Bloom's Taxonomy verbs.

Bloom's level	Verb	Count	Per cent of total
Remember	State	107	22.5%
	Select	85	17.9%
	Indicate	73	15.4%
	Record	35	7.4%
	Know	31	6.5%
	Total	331	69.7%
Understand	Manage	471	35.3%
	Show	127	9.5%
	Report	120	9.0%
	Describe	90	6.8%
	Review	83	6.2%
	Total	891	66.8%
Apply	Practice	186	18.0%
	Show	127	12.3%
	Compute	124	12.0%
	Operate	111	10.7%
	Give examples	80	7.7%
	Total	628	60.7%
Analyze	Experiment	185	29.5%
	Test	138	22.0%
	Question	54	8.6%
	Analyze	41	6.5%
	Criticize	41	6.5%
	Total	459	73.1%
Evaluate	Evaluate	136	20.6%
	Assess	96	14.6%
	Score	92	14.0%
	Select	85	12.9%
	Rate	73	11.1%
	Total	482	73.2%
Create	Perform	226	28.8%
	Set up	105	13.4%
	Plan	63	8.0%
	Propose	63	8.0%
	Organize	50	6.4%
	Total	507	64.6%

Foundational Educational Theory Content Analysis

Nine foundational educational articles were identified for the theories integrated in the construction literature. Content analysis by autonomous counting was conducted with NVivo 12 to evaluate the article contents to determine recurring themes that occur across the literature. **Table 5** presents the results of the content analysis in the alphabetical order for Ajzen's theory (Ajzen, 1985), self-efficacy (Bandura, 1977), visual pedagogy (Fransecky and Debes, 1972), blended learning (Garrison and Kanuka, 2004), the Kirkpatrick model (Kirkpatrick, 1959),

TABLE 4 | Frequency of terminology in evaluated studies by term type.

Type	Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
Training/Education	Behavior	1	2	2	-	1	-	18	-	-	-	-	-	-	-	37	61
	Experience	3	7	4	3	5	-	1	1	1	1	6	2	2	7	7	50
	Group	-	3	20	3	2	-	1	-	8	2	2	3	1	1	-	46
	Knowledge	3	12	12	3	2	5	-	1	5	1	5	2	1	4	1	57
	Learning	23	15	-	10	7	4	-	1	1	1	16	19	8	20	-	125
	Simulation	1	4	-	1	12	-	-	-	-	-	18	8	-	2	-	46
	Study	3	11	3	1	3	5	4	1	2	2	9	1	3	3	7	58
	Training	12	33	7	55	12	5	4	8	17	19	16	-	9	16	3	216
	Total																659
General	Construction	15	17	9	21	9	10	11	8	18	9	3	19	9	13	34	205
	Contractor	-	-	-	1	-	1	2	1	-	2	-	-	-	-	36	43
	Data	4	17	2	1	1	2	4	1	-	2	3	-	1	6	2	46
	Environment	9	6	-	4	3	4	3	-	-	-	7	2	1	17	-	56
	Industry	2	7	6	1	5	2	3	-	1	-	1	3	4	3	9	47
	Management	-	2	1	-	2	7	12	-	-	2	5	16	-	4	28	79
	Materials	4	1	1	10	1	1	3	1	9	1	-	-	2	1	15	50
	Methods	5	15	-	2	2	4	5	3	1	2	4	1	3	2	9	58
	Project	-	1	-	-	-	1	5	1	6	1	1	6	-	14	12	48
	Research	2	23	-	-	2	2	7	2	5	-	6	3	4	2	2	60
	Site	4	3	-	1	-	2	10	2	3	4	2	1	-	7	3	42
	Workers	19	9	5	33	14	20	5	18	18	21	7	5	8	13	1	196
	Total																930
Topic area	Injury	4	5	2	3	17	1	6	11	-	10	-	-	-	-	-	59
	Safety	-	31	24	18	10	5	34	4	13	8	-	-	-	2	-	149
	Waste	-	-	-	-	-	-	-	-	-	-	-	-	-	-	69	69
	Total																277
Total		114	224	98	171	110	81	138	64	108	88	111	91	56	137	275	1866

TABLE 5 | Frequency of terminology in foundational education literature.

	Ajzen (1985)	Bandura (1977)	Fransecky and Debes (1972)	Garrison and Kanuka (2004)	Kirkpatrick (1959)	Knowles (1980)	Prensky (2003)	Shiffrin and Atkinson (1969)	Watson (1913)	Total
Activities	1	3	8	1	1	8	-	-	2	24
Behavior	26	15	3	-	-	-	-	2	11	57
Change	-	11	-	6	1	3	1	3	-	25
Effects	3	9	-	4	1	-	3	19	2	41
Experience	1	6	16	4	-	9	1	-	-	37
Information	1	3	4	4	2	-	1	35	-	50
Language	-	-	22	-	-	-	1	-	3	26
Learning	-	2	3	16	1	18	4	8	1	53
Memory	-	1	1	-	-	-	-	42	1	45
Model	1	9	3	1	-	2	-	11	-	27
Performance	2	23	1	-	1	-	-	4	-	31
Process	1	3	2	2	-	9	1	22	4	44
Response	5	11	1	-	-	-	-	26	3	46
Search	-	-	-	-	-	-	-	28	-	28
Subject	14	4	2	1	4	2	3	1	1	32
Tasks	-	10	1	1	-	8	-	13	-	33
Visual Literacy	-	-	23	-	-	-	1	-	-	24
Total	55	110	90	40	11	59	16	214	28	623

andragogy (Knowles, 1980), digital game-based learning (Prensky, 2003), long-term retention (Shiffrin and Atkinson, 1969), and behaviorism (Watson, 1913). The same reporting threshold implemented for the previous content analysis was used for these articles, resulting in terms appearing at least 24 times across the nine articles being reported.

Content Analysis Comparison

Approximately, one-third of the terms in **Table 4** consists of terms related to education, while all terms in **Table 5** are associated with the field of education. While the reviewed studies are within the realm of the construction industry, they do focus on training. As such, one may expect a similar emphasis on education-related terminology. Instead, the absolute frequency of education-related words in the construction studies (659; 44 terms per article) is close to that in the foundational literature (623; 69 terms per article).

The terms learning, behavior, and experience appear in both **Tables 4**, **5**. Further analysis reveals that in **Table 4** across all studies. Of the 1866 commonly occurring terms in **Table 4**, the occurrence frequency for "learning" is 125 (6.7% of the total), for "behavior" is 61 (3.3%), and for "experience" is 50 (2.7%). This is contrasted with **Table 5**, where the occurrence frequency for "learning" is 53 (8.5% of the total), for "behavior" is 57 (9.1%), and for "experience" is 37 (5.9%).

DISCUSSION

Study Selection and Training Case Review

The majority of studies that met the inclusion criteria were on the subject of safety, indicating a lack of education theory–embedded training for construction means and methods. Only three studies focused on managers or designers, while the remainder of the studies focused on workers. Seven articles were published in the 4-year period 2017-2020, while eight articles were published in the preceding nine years (2008-2016), indicating an increasing focus on education theory–integrated construction industry training research. Six of the fifteen studies (40%) integrated andragogy in the training. Andragogy is the study of facilitating adult learning, in contrast to pedagogy, the study of facilitating child learning (Knowles, 1980). The heavy utilization of this theory across the studies is potentially due to the fact that construction industry professionals are adults and using an educational theory specifically tailored to that group is an obvious choice when designing educational theory-integrated training programs. Seven of the fifteen studies were conducted in the United States, with two in Australia, and one each in Malaysia, Italy, Brazil, China, United Kingdom, and Ireland.

Bloom's Taxonomy Frequency

Bloom's Taxonomy is designed on a hierarchical scale, meaning that each level is built on the assumption that each higher level subsumes the lower levels that precede it. This implies that learners at higher levels should meet objectives pertaining to the higher levels of the taxonomy such as the analysis, evaluation, or creation levels. From **Table 1**, the hierarchical levels of Bloom's Taxonomy begin with "understand" or the ability to recall and ultimately move toward creation, which is the ability to put components together to form a whole. Based on this theory, as learners reach higher levels, terms from higher categories should be used more frequently, while terms from lower levels should be used less frequently.

Across the fifteen studies, mixed results are observed in the Bloom's Taxonomy verb frequency, where are from the greatest to least frequency: understand (891), apply (628), create (507), evaluate (482), analyze (459), and remember (331). Both "understand" and "apply" are lower order skills, while the higher order terms have less frequent usage, in no discernible order, and finally, terms associated with "remember" are used least frequently. One can assume that the target audience of a training or educational experience should have mastery of lower order skills. This leads to the use of the higher order skills such as analyze, evaluate, and create. However, no consistent pattern in student learning objectives is observed, indicating that assumptions of the target audience must vary across the studies or that Bloom's Taxonomy objectives were not explicitly considered. From this evaluation, one cannot determine whether the trainings analyzed were designed assuming participants had little to no exposure to the subject of training or if they had moderate exposure and were ready to move onto higher order skills.

Training and Foundational Educational Theory Content Analysis and Comparison

The content analysis revealed that relatively few common terms across the studies were explicitly linked to education. This is surprising given that the underlying topic of the identified articles is training in the construction industry. For foundational articles of the educational or learning theories cited by the studies, all of the most frequent terms are connected to the field of education, indicating a marked difference between the frequency of the words in **Tables 4**, **5**. This disparity is further evidenced by the difference in relative frequency of occurrences of the terms learning, behavior, and experience described in the results section.

Observations

Observations were made regarding the studies that met the inclusion criteria. Overall, two-thirds of the studies focus on safety, while 100% of the studies from the United States reflect safety training. This indicates that the primary focus of training for current construction industry professionals is safety and that little focus is given to other subjects of construction. This observation begs certain questions. Why the topic of safety is disproportionately represented in the literature above other topics? Although safety is ubiquitous, are safety professionals more likely to integrate educational theory into training and publish their findings in the literature? This observation is rather remarkable and warrants further investigation, especially in light of the shortage of skilled construction professionals discussed in the Introduction.

CONCLUSION

This article provides a state-of-the-art review of educational theory-integrated construction industry training. Inclusion criteria were established to identify relevant peer-reviewed articles published after 2005 for investigation. After identifying 15 relevant studies, case review was conducted to summarize the educational theories employed, training subjects, and target audience. The frequency of Bloom's Taxonomy verbs were enumerated and summed across the identified studies. Content analysis was conducted on the identified studies, and the foundational literature for the educational theories identified by those studies to identify the most frequently used terms, which were compared for similarities and differences. The findings of this study are as follows:

- Fifteen studies were found that met the inclusion criteria; of these, two-thirds (2/3) focused on worker safety.
- Andragogy was the most often integrated educational theory, used in 40% of the studies.
- Three studies that met the inclusion criteria (20%) focused on managers or designers, while 80% of the studies focused on workers.
- More than 27% of the Bloom's Taxonomy verbs in the identified studies are associated with the second lowest level, "understand."
- Less than 35% of the most frequent terminology in the identified studies was categorized as educational.
- All frequently used terms in the foundational educational theory literature were considered educational.
- Common educational terminology between the studies and foundational educational theory analyzed appear at higher rates in the foundational literature.

Overall, this study found that not many construction industry training programs have been published in the archival literature. It is surprising that so little attention has been paid to scholarly research to education theory–integrated construction training programs, given the impact that construction has worldwide. Certainly, training program exists through certain industry organizations; however, information about these types of programs was not apparent in the literature. Further, as workers, managers, and designers progress in their careers and technology evolves, there is a need for continuing education to keep these individuals abreast of recent changes. This appears to be an opportunity to address this lack of training in the construction, and this article can serve as a starting point for those wishing to develop. Given the tremendous need for quality construction training worldwide, this study serves as a starting point in the improvement of further industry training by providing a comprehensive review of documented educational theory–integrated construction training.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, and further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

HJ conducted the literature review, collected and analyzed, and developed the initial text. CF provided original ideas and advice on the overall project methodology and edited the text. CB proposed the research methodology and provided the conceptual design of this research. IN, CP, and YZ edited the text and provided regular feedback and guidance.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2021.635978/full#supplementary-material

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Facilitating Digital Transformation in Construction—A Systematic Review of the Current State of the Art

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There is increasing implementation of digital technologies in construction. However, the transformation effects encompassing digital technology implementation are yet to be fully comprehended within the context of construction. Therefore, this study was aimed to provide a holistic understanding of digital transformation in construction. The study drew on extant literature by studying 36 journal publications published between 2016 when digital transformation emerged in construction from the information systems field and 2020. This led to the development of an inductive framework using a grounded theory methodology (GTM) to highlight digital transformation in construction as a process where the implementation of digital technologies creates transformation effects that trigger strategic considerations for putting in place the enablers that facilitate transformation effects and for suppressing the barriers to it. Building on the framework, this study described and presented the strategic considerations for facilitating specific enablers and those for suppressing specific barriers as digital transformation guideline in construction. This study demonstrated how the implementation of digital technologies has increased the understanding of and provided the basis for digital transformation in construction.

Keywords: digital transformation, construction, strategic considerations, enablers, barriers

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INTRODUCTION

The construction industry is experiencing an increasing implementation of digital technologies such as building information modeling (BIM), augmented and virtual reality (AR/VR), laser scanning, robotics, 3D printing, prefabrication and DfMa platforms, analytics software, blockchain, digital twins, internet of things (IoTs), and machine learning solutions throughout the built asset lifecycle (e.g., project, organization, and industry levels) (Ibem and Laryea, 2014; Koch et al., 2019; Singh, 2019). From the overview of academic research, research analysis reveals not only an increasing implementation but also an adaptation of digital technologies for construction operations (Oesterreich and Teuteberg, 2016; Morgan, 2019; Pan et al., 2020; Zabidin et al., 2020). Globally, industry practitioners comprising construction professionals, construction companies, professional bodies, and government agencies have expressed their preferences for implementing digital technologies in construction. McKinsey & Company reports that top players in the construction industry agree that digital technologies are critical to their sustenance (Buisman, 2018), and the innovative ones are aggressively implementing them (KPMG, 2019). Some of these technologies, such as BIM, have become the norm in the construction project delivery and on the path to maturity in many companies (Maskuriy et al., 2019b; Zabidin et al., 2020).

The implementation of digital technologies encompasses transformational effects—known as digital transformation (DT). Conceptually, DT refers to the changes (or disruptions) that the

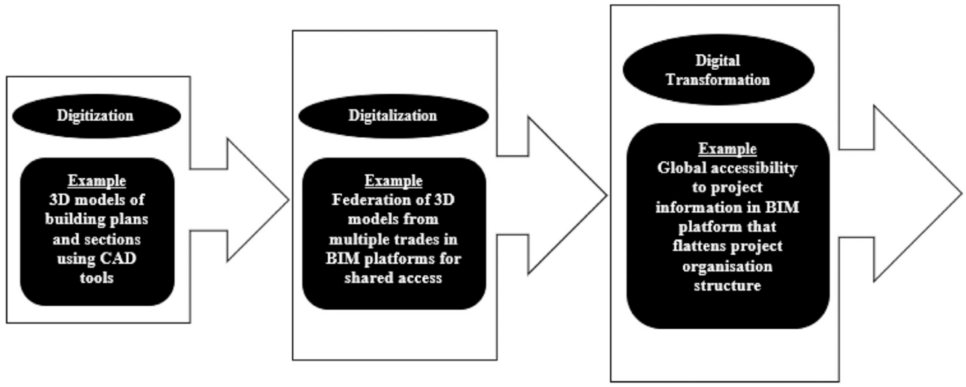

FIGURE 1 | Illustration of digitization–digitalization–digital transformation.

implementation of digital technologies brings to existing business models, which may be experienced in the construction production process, construction companies, and the construction supply chain (Hausberg et al., 2019; Nadkarni and Prügl, 2020). The transformation effects of digital technologies distinguish DT from digitization—which is only the conversion of analog information (e.g., texts, photos, and sounds) into digital information (or binary numbers) that can be encoded by the computer—and digitalization—which is the broader use of digital technologies to optimize existing business processes and functions through enhanced coordination to create more business opportunities and customer value (Verhoef et al., 2019; Berlak et al., 2020). In construction, an example is the old 2D designs on paper, which can now be modeled in 3D using computer-aided designs (CAD) (digitization). Another example is the federation of CAD designs from different trades into the BIM common platform that enables improved project procurement through shared access, clash detection, scheduling, costing, and analytics (digitalization). Lastly, the integration of clients in the building procurement process through augmented interaction with 3D or higher models or flatter project–organization structure that results from global access to project information in the BIM platform or the evolution of new competencies such as construction informatics are typical examples of transformations resulting from the implementation of digital technologies in construction (DT). Based on the examples, digitization–digitalization–DT appears to be in progression from a preceding one to a succeeding one. In fact, it has been suggested that digitization and digitalization are required to attain DT (Verhoef et al., 2019) (see **Figure 1** illustration).

It is notable that the construction industry is close to a "grand" digital technology implementation (Murray, 2018; Autodesk, 2020), but attempting to progress toward DT will not be easy. DT is about introducing digital technologies and implementing the correct technologies by assessing the business needs, strategizing for the future needs, and developing a roadmap to the future (Murray, 2018; Shapiro et al., 2019). Therefore, there is a need to employ a strategic implementation of digital technologies to facilitate the enablers of DT while suppressing the barriers against it in construction (Pan et al., 2020). Full-scale DT has a wide range of benefits at the industry level (through increased productivity and market share), organizational level (through sustained competitiveness and lowered costs in construction companies), and project level (through improved project performance and safety) in construction (Agarwal et al., 2016). In terms of the monetary estimate, these benefits can sum to USD$1.2 trillion in the residential sector alone by 2025 (Gerbert et al., 2016). Meanwhile, DT is not all about positive outcomes. Negative outcomes such as loss of investments, loss of jobs, and loss of the identity of the construction industry to digital technologies are possible, particularly in a construction industry characterized by fragmentation, lack of replication, transience, and decentralization, making DT very challenging (Koeleman et al., 2019). Therefore, DT must be attempted correctly to maximize the benefits and minimize the negative outcomes.

With the recent aggregation of the literature revealing an increasing implementation of digital technologies (Maskuriy et al., 2019a; Maskuriy et al., 2019b; Zabidin et al., 2020), the transformational effects of these technologies will begin to materialize as DT in construction. Meanwhile, current research on DT in other fields of knowledge such as information systems (IS) (Vial, 2019), business economics (Reis et al., 2018), and interdisciplinary management (Henriette et al., 2015; Verhoef et al., 2019; Nadkarni and Prügl, 2020) has not provided an adequate understanding of DT in construction. Therefore, how construction stakeholders can respond and adapt to DT is not currently known. This study aimed to take stock of the current knowledge through a literature review to provide an understanding of DT in construction. It is hoped that this study will aid construction stakeholders' response and adaptation to DT in construction. The first research objective is to propose an inductive research approach that employs a GTM to review the literature. The approach provides an explorative guideline of research on DT in construction. The second objective is to identify and describe the following: the strategic considerations for implementing digital technologies in construction, the enablers that facilitate DT in construction, and the barriers that suppress it. The third objective is to present and describe an illustrative framework of how the strategic considerations facilitate and suppress specific enablers and barriers of DT in construction, respectively. This study offers two contributions. The first one is a review that integrates current knowledge on DT in construction. The second one is providing avenues for developing a guideline for DT in construction.

BACKGROUND

Digital Transformation Concept

The increasing use of digital technologies such as virtual reality gadgets and smartphones and their tendencies to disrupt existing business practices and competition landscapes and causing changes to end users' behaviors in response to the technologies has been the bedrock underpinning the conceptualization of digital transformation (DT) in the literature. There is a wide range of digital technologies that are implemented in construction, and they can be divided into four components, including digital data, automation system, digital access, and connectivity (Dallasega et al., 2018; Heusler and Kadija, 2018). Digital technologies generate data when used (Vial, 2019); for instance, wearable sensors and smart meters are used as a collection point of *digital data* in construction (Craveiroa et al., 2019). The *automation* systems use digital technologies to create self-organizing systems such as robots for lifting objects on sites (Berlak et al., 2020) and blockchain for executable payment to contractors (Li et al., 2019). Deriving from automation systems is *digital access*, which is the opportunity afforded by mobile access to internet networks to execute solutions in real time such as data analytics and processing to make on-the-spot decisions or make future predictions (Berger, 2016; Buisman, 2018; Maskuriy et al., 2019b). *Connectivity or network* encompasses the linking and synchronizing separate activities such as 3D model development and energy-use simulation in the BIM platform (Keskin et al., 2020) or linking the physical-to-digital-to-physical in construction using sensors, cloud computing, IoT, augmented reality, and virtual reality (Craveiroa et al., 2019). Originally, DT evolves from the domains of business transformation strategy and IS (Ismail et al., 2017). Business process transformation establishes new ideas, concepts, opportunities, and competitive strategies to drive business processes, while the IS domain employs information and communication technology to trigger business transformations. As this evolution germinates over the years, the impact has brought about radical changes in business management in the project and organizational contexts (Morakanyane et al., 2017). The changes have been coined into the buzzword known as digital transformation (DT). DT can be regarded as adopting digital technologies to optimize business performance (Henriette et al., 2015). Meanwhile, it is not just about technologies but the changes taking place due to the adoption of digital technologies (Verhoef et al., 2019). The changes or effects are often the creation and addition of value to the existing business (Hausberg et al., 2019) and sometimes a reduction in business value. The addition of value could improve customer experiences of digitally enabled products and services (Verhoef et al., 2019), enhance employee skills and talents (Ismail et al., 2017), and achieve competitive business models (Morakanyane et al., 2017; Reis et al., 2018). DT can also be defined in terms of the individual, organizational, societal, and industry levels where disruptions resulting from digital technologies' adoption occur. As the proliferation and adoption of digital technologies trigger disruptions in the general society or a specific industry, businesses adopt digital technologies to alter their value creation process in response to the disruptions. Therefore, DT is a process whereby digital technologies play a crucial role in creating and reinforcing disruptions around with strong consequences for business performances (Ismail et al., 2017; Reis et al., 2018). Given the wide range of the digital technologies, DT guideline for implementing them correctly should be put in place to maximize their transformation impacts in construction.

METHODOLOGY

An inductive approach to the literature review was selected in line with the aim of taking the current stock of knowledge to provide an understanding of DT in construction. This study followed the procedures advocated by Sutrisna and Setiawan (2016a) and Wolfswinkel et al. (2013) by employing their procedural steps adapted from grounded theory methodology (GTM) analysis to review the literature. As illustrated in **Table 1**, the guidelines are divided into six steps and thirteen substeps that guided the review process, from the definition of the scope of review to the presentation of findings. In the approach, the outcome in a step is used to perform the succeeding step (Hausberg et al., 2019) to ensure a transparent and replicable process of analyzing the literature on DT in construction (Nadkarni and Prügl, 2020).

Step 1—Setting the Scope of the Review

The scope of this review is to focus on the research contributions to DT in the construction domain. DT is basically the impact of digital technology implementation, and it is still unveiling in both practice and research in the construction sector. Therefore, focusing on this sector only helped to be sensitive to emerging concepts in the analysis and obtain in-depth understanding, instead of focusing on research contributions across multidisciplinary sectors, such as the work of Verhoef et al. (2019). Meanwhile, it was recognized that the construction operates at multiple levels, mainly the project, organizational, and industry levels. These levels were included in the preliminary/descriptive analysis to avoid contextual bias. Also, due to the emerging nature of the subject, no specific time frame was set in the scoping to allow the date of research publications to emerge from the data.

Step 2—Selecting Sources of Research Contributions

In this step, Google Scholar, Scopus, and Web of Science (WoS) have been identified as the databases to source for data. One of the reasons was that these databases are domain sensitive; they cover more quality research publications than other online sources

TABLE 1 | Grounded theory methodology style of analysis for literature review.

Step	Task(s)
Step 1—Setting the scope of the review	• Define a domain of research
Step 2—Selecting sources of research contributions	• Identify a database to source data • Select the type of publication
Step 3—Selection of keywords	• Identify a criterion for the search term
Step 4—Screening process	• Search databases using the search term • Scan publications • Filter publications • Repeat search query • Download publications
Step 5—Eligibility	• In-depth analysis using inclusion/exclusion criteria
Step 6—Coding structure and analysis	• Open coding • Axial coding • Selective coding

(Chadegani et al., 2013), especially construction research publications (Maskuriy et al., 2019b). Within these databases, peer-reviewed journal publications were the main targets. Compared to conference papers and practitioner reports, construction journal publications undergo a more rigorous peer-review process. They, therefore, provide a more valid and reliable conceptualization of a subject, especially one that is still emerging as DT in construction. Consequently, academics and practitioners typically prefer the journal type of publication to disseminate new findings (Henriette et al., 2015).

Step 3—Selection of Keywords

In this step, a preliminary search in the Google scholar database was made to identify the keywords and search terms for the review. It was observed that DT is the generic keyword used in multidisciplinary disciplines (Verhoef et al., 2019), but it is also used in describing the impact of implementing digital technologies in the construction sector [e.g., (Bonanomi et al., 2019)]. Therefore, a criterion for the search term that includes a general keyword to account for the impact of the implementation of digital technologies ("digital transformation") and a domain-specific keyword ("construction") was adopted. The search terms using the combination of "digital transformation" AND "construction" were designed to collect data. It was acknowledged that keywords such as "digitization" and "digitalization" could be relevant but the search term combination adequately fits the criterion specified.

Step 4—Screening Process

The search process using the keywords search combination in the databases generated up to 5797 publications in July 2020. This is a large number caused by the broad keywords, especially "construction," which can convey other meanings than describing a sector (semantics). The publications were scanned by title followed by reading the abstracts of those relevant to the aim of the study (Wolfswinkel et al., 2013; Verhoef et al., 2019). Because multiple databases were employed, duplications and peer-reviewed publications that are not journals were filtered. Examples are conference papers published in ScienceDirect procedia and Springer publication outlets. Part of the filtration was removing those publications not written in English to prevent us from wrong interpretations (Reis et al., 2018). After reading the abstracts and the filtration, it narrowed down to 151 publications. Before downloading the publications in the PDF format in the Endnote, the search query was repeated against them to check that they are rightly included for a more in-depth review (Chadegani et al., 2013).

Step 5—Eligibility

As mentioned above, the 151 publications were subjected to a more in-depth study and analysis using more rigorous inclusion/exclusion criteria to select publications that qualified for the final sample as follows: 1) publications were required to primarily focus and contribute to DT in the construction sector, including the project, organizational, and industry levels of construction operation [e.g., Bonanomi et al. 's (2019) study on the impact of DT on the organizational structures in large AEC firms]; 2) publications were required to use DT as the theoretical lens of research and may use this theoretical lens: propose hypotheses; identify the research variables; for data collection; for explaining research findings; and to drawing conclusions and recommendations; and 3) publications that are neither 1) nor 2) were excluded; such publications are more practitioner-centered offering insights on the implementation of digital technologies to relevant stakeholders [e.g., Deraman et al., 2019; Soman and Whyte, 2020; Zima et al., 2020]. The eligibility process resulted in a final sample of 36 journal publications that met the criteria. The publications within the sample were published within a time frame from 2016 to 2020, 35 of which were published between 2018 and 2020. This indicates that research on DT in construction is just emerging, deriving from DT as a topic of research that has only emerged about 5–10 years ago from the broader field of IS (Ismail et al., 2017; Nadkarni and Prügl, 2020).

Step 6—Coding Structure and Analysis

Following Wolfswinkel et al.'s (2013) suggestion, each publication within the final sample was randomly picked to code the contents using the coding structure in **Table 2**.

The coding structure is divided into two parts. The first one is the descriptive information of the journal publications comprising three categories, namely, publication field, nature,

TABLE 2 | Coding structure of the final sample.

Coding structure			
Descriptive information of journal publications	Publication field	Construction	Information technology journals in construction Generic/common construction journals
		Information technology Economics Health	
	Nature of the study	Empirical	Quantitative studies Qualitative studies
		Conceptual	
	Context of the study	Industry Organisational Project	
Concepts/main points of focus		Strategic considerations	Process Collaboration Learning Value Lifecycle
		Enablers	Choice of digital Data Digital champions Attraction of digital Training opportunities Innovativeness System support Organization structure Digital culture Legitimation Research
		Barriers	Data processing Data access and ownership System integration Standardization ROI uncertainty Owner buy-in Older workers Business models Digital divide System attacks

and context of the study. The categories are subdivided into children categories that provide deeper information about the publications. Most of the sources are journals aimed to produce publications on information and technology in construction (36%). Without undermining the scoping process, five publications from nonconstruction journals (including *Computers in Industry,* where three publications were sourced) included in the sample are consistent with the selection criteria. These publications indicate an interest from other disciplines in DT in construction. Furthermore, 58% (21) of the journal publications are empirical studies employing quantitative or qualitative research methodologies, while the rest (15 or 42%) are conceptual studies. While this contradicts previous findings in research on DT in other fields (Nadkarni and Prügl, 2020; Reis et al., 2018), it suggests more attempts at testing the existing theoretical foundations on DT in construction. Studies seeking to conceptualize the field such as this study are necessary to match the enthusiasm for empirical testing of DT in construction. Finally, consistent with wider implications of DT in different contexts (society, organization, industry, and project contexts) (Keskin et al., 2020; Bharadwaj et al., 2013; Morakanyane et al., 2017), 55% of the publications focused on DT in the construction industry context, 28% on the project context, and 17% on the organizational context. Interestingly, most conceptual studies (13/15 or 87%) focused on the construction industry context. It further reinforces the emerging nature of research on DT in construction, commencing with more research conceptualization of field (conceptual studies) from a higher context, which is the construction industry context.

The second one is the coding structure for the concepts or main points of focus in the sample. It is comprised of three categories, namely, strategic considerations, enablers, and barriers of DT in construction. Similarly, the categories are subdivided into children categories. In this step, the techniques borrowed from the GTM were applied to analyze the texts in the final sample carefully (Böhm, 2004; Sutrisna and Setiawan, 2016b) to develop an understanding of the literature under review (Vial, 2019). Therefore, the three techniques of GTM (open coding, axial coding, and selective coding) were performed. Open coding is the conceptualization and categorization of phenomena through an intensive analysis of the data. Axial coding is exploring and identifying the relationships between

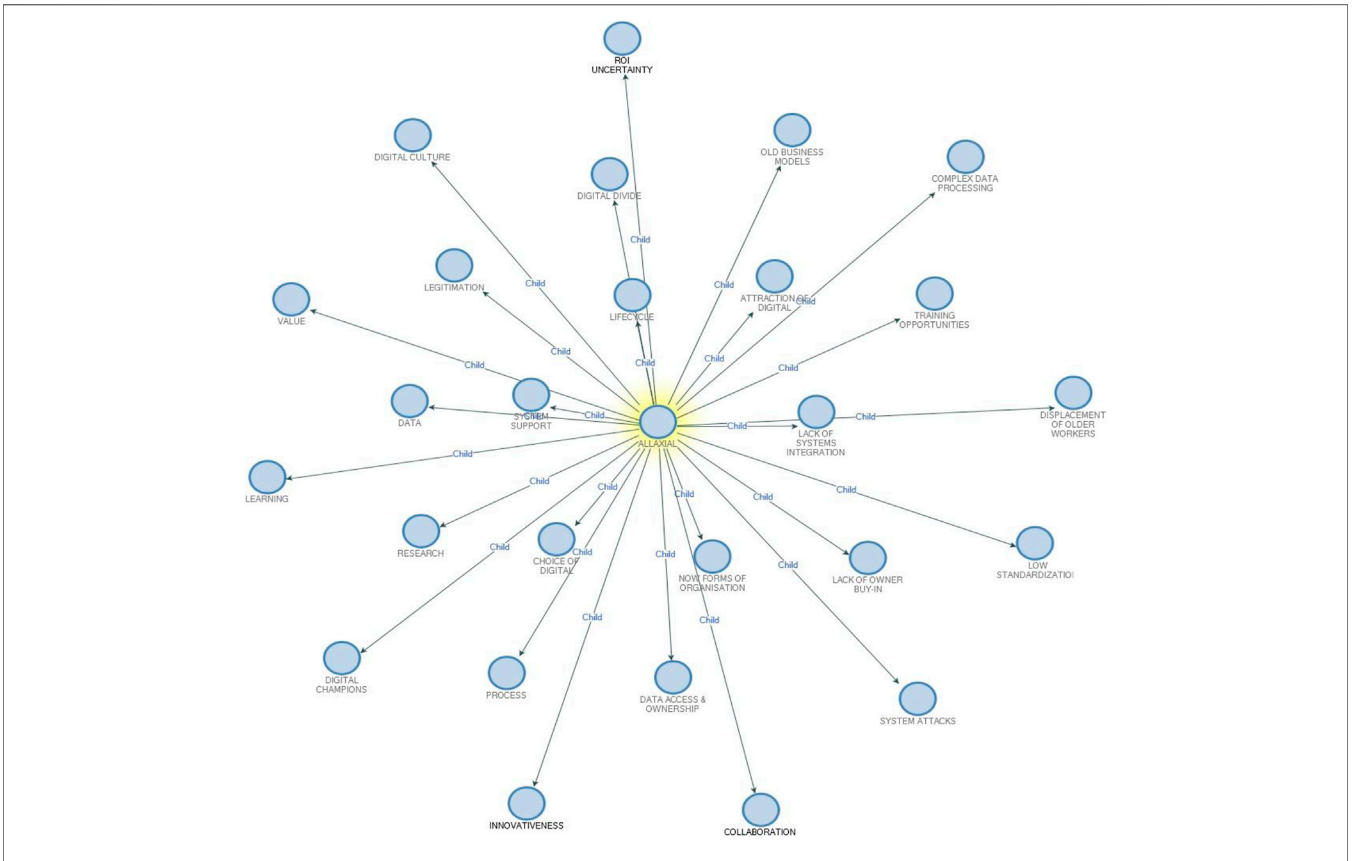

FIGURE 2 | NVivo explore diagram of the second-order categories.

concepts and categories that have been developed in the open coding process. Selective coding is the integration of the different categories that have been developed, elaborated, and mutually related during axial coding into one cohesive whole. Of note is that selective coding is quite like axial coding, except that it is carried out on a more abstract level.

The open coding was carried out by interrogating the main text in the 36 publications regarding the findings, discussions, concluding parts, and other relevant parts, while also taking notes to summarize each publication in the NVivo software (Hull, 2013; Sutrisna and Setiawan, 2016a; Nadkarni and Prügl, 2020). This led to the first abstraction of the concepts in the sample. Four hundred and twenty-three (423) first-order categories through the open coding were identified at this point. In the following axial coding, there was a search for the meanings and patterns in the open codes to assemble them into second-order categories in the NVivo. As an example, the first-order categories such as "concerns about the exchange of information" and "inconsistent standards" were placed under a second-order category coded "Low standardization." Consistent with GTM to ensure a gradual discovery, the publications and open codes were revisited iteratively and noting new insights in a separate document. The coding instances were much reduced after a round to retain the 26 second-order categories through axial coding and presented using the NVivo Explore Diagram in **Figure 2**.

Selective coding was the last technique that represented the highest level of abstraction in our coding, where we endeavored to integrate the second-order categories. It is at this point that we further reduced the 26 second-order categories into three main categories. They are strategic considerations, enablers, and barriers of DT in construction and illustrated in **Figure 3**.

In line with the GTM, the analysis was designed to ascend from one level of abstraction per time, commencing with the descriptive information of the sample, followed by the storyline or node summary of the main categories and children categories of the concepts or main points of focus in the sample (open coding, axial coding, and selective coding). Finally, the mapping tree of the interaction of the categories is presented to discuss the findings. This analysis procedure is represented in **Figure 4**. Furthermore, as mentioned previously, memoing new insights in a separate document in the iterations in the coding process was carried out (Webster and Watson, 2002; Hull, 2013; Sutrisna and Setiawan, 2016b).

Meanwhile, a separate analysis of the publications was carried out to reveal construction activity fields and their digital transformation using an inductive content analysis method. This method was used in conformity with the earlier inductive approach to literature review (or data collection) due to the emergent nature of the subject of investigation (Kyngäs, 2020). The first step involved data reduction—where the first author

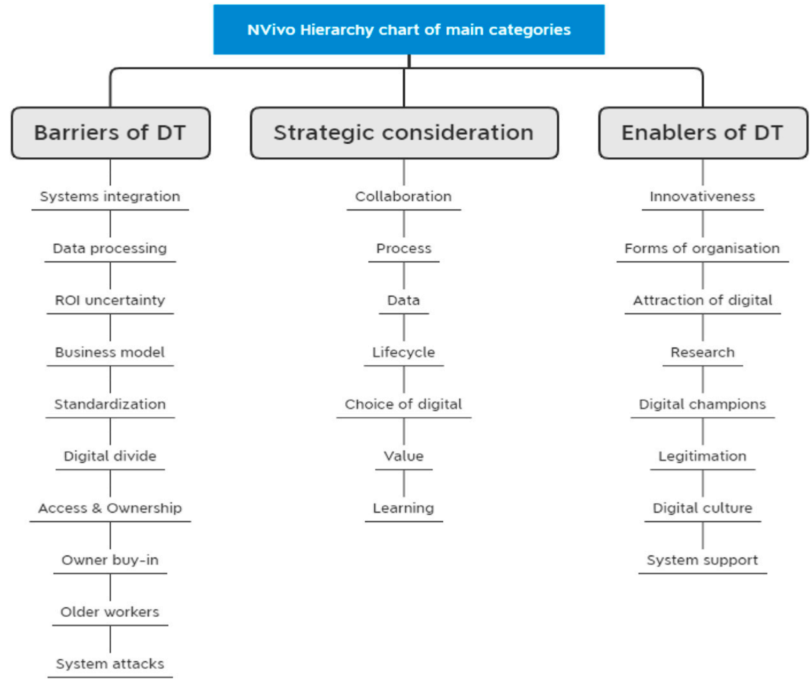

FIGURE 3 | NVivo hierarchy chart of the main categories (redesigned by authors).

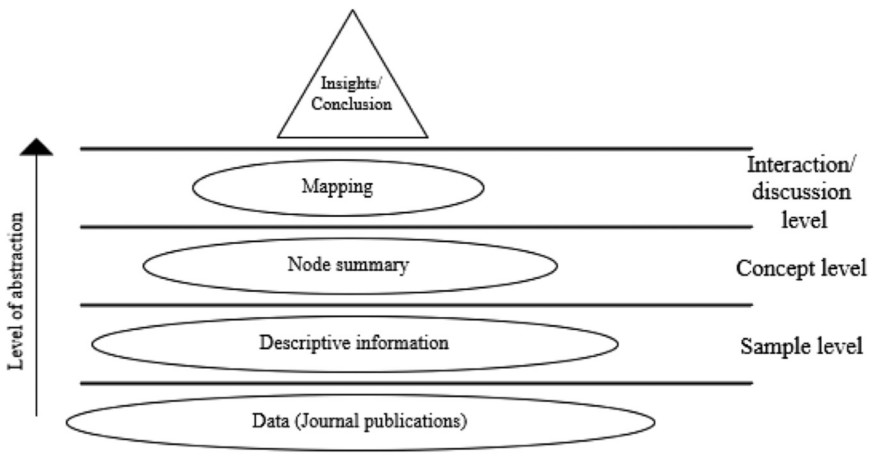

FIGURE 4 | Analysis procedure.

carried out further reading of the 36 publications to identify and select the ones that focused on the implementation of specific digital technologies in their analysis. For instance, Craveiroa et al. (2019) focused on the application of 3D printing for architectural and engineering designs and was selected. Aghimien et al.'s (2020a) study was not selected for exploring digital partnering from professional perspectives only. Of the 36 publications, 19 of them met this criterion and were selected. The second step involved data grouping where the second author, an experienced researcher in qualitative studies [e.g., Sutrisna and Setiawan, 2016b], identified construction activity fields that were implemented in the 19 publications. This author used MS Excel to tabulate the digital technologies in "rows" and "construction activity fields" in columns for cross analysis and descriptions. The construction activity fields refer to project-based tasks such as physical construction (Koseoglu et al., 2019) and organization processes such as interfirm relations (Hetemi et al., 2020) that feature in project delivery and asset lifecycle. The last step involved formation of concepts. Both the authors were involved, using the table produced in the previous step to extract the applications of digital technologies to specific construction activity fields in the publications. There was need

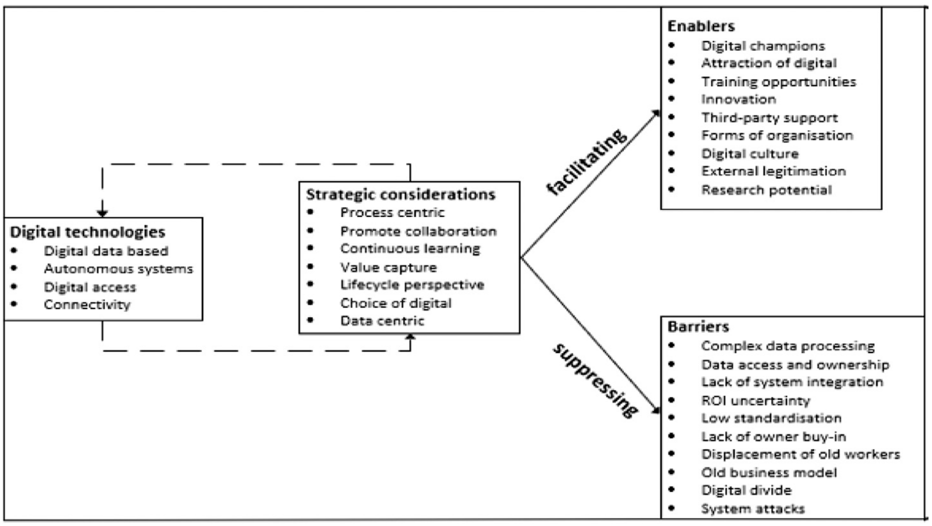

FIGURE 5 | Concepts of DT in construction.

to reconcile construction activity field of application of a digital technology, for instance, whether BIM is applicable to either one or both supply chain integration and interfirm relations (Hetemi et al., 2020). The authors extracted both activity fields and retained because the same digital technology (e.g., BIM) was applied to the activity fields in other publications in the sample [e.g., Berlak et al., 2020].

FINDINGS

Inductive Framework of Digital Transformation in Construction

The inductive framework condensing the existing knowledge on DT in construction is presented in **Figure 5**. As mentioned in step 6 in the methodology section, the framework illustrates the concepts of DT in construction emerging from the open coding, axial coding, and selective coding of the sample as follows. First, DT is the process where the implementation of digital technologies creates transformational effects. Second, the transformation effects trigger strategic considerations from the implementers of digital technologies, which, third, helps to 1) put the enablers that facilitate transformation efforts in place and 2) suppress the barriers to the transformation efforts.

Strategic Considerations of Digital Technologies in Construction

Successful DT requires strategic consideration of digital technologies (Buisman, 2018; Aghimien et al., 2020a). As shown in **Table 2** and **Figures 2**, **3**, the results of the open coding, axial coding, and selective coding produce seven strategic considerations for implementing digital technologies, namely, process, collaboration, learning, value, lifecycle, choice of digital, and data. Of note, these considerations point mainly to "how" digital strategies may be developed to implement digital technologies in construction rather than specifying actual digital strategies. They are described in this section, and the summary of the literature on the strategic considerations is presented in **Table 3**.

Process

Process-centric strategic consideration suggests systematic implementation of digital technologies and has been found to foster DT in construction (Li et al., 2019; Aghimien et al., 2020b). This strategic consideration aligns the implementation of digital technologies procedurally with the construction project lifecycle phases (Koseoglu et al., 2019; Morgan, 2019), for instance, initially implementing BIM in the design and construction phases and later implementing the tool at the building operation phase. A study revealed that the process-centric strategy was employed in the blockchain implementation, which proceeded in a controlled manner according to project lifecycle phases (Li et al., 2019). In this manner, the impacts resulting from the blockchain implementation, such as bypassing extant regulations, were better controlled and evaluated (Li et al., 2019). Also, digital technologies can be very disruptive. The process-centric strategic consideration allows an incremental implementation of digital technologies, which helps control the rate of diffusion of implemented technology before reaching the disruptive stage (Deraman et al., 2019; Morgan, 2019).

Collaboration

The strategic consideration for digital technology implementation should promote collaboration and interaction among stakeholders in the construction supply chain (Dallasega et al., 2018; Craveiroa et al., 2019; Keskin et al., 2020). With respect to BIM, a recent study found that most stakeholders who implement it are still immature and often struggle with basic

TABLE 3 | Summary of literature on strategic considerations.

Strategic considerations	Sources
Process (n = 11)	Goulding et al. (2018), Heusler and Kadija (2018), Woodhead et al. (2018), Braun and Sydow (2019), Craveiroa et al. (2019), Koseoglu et al. (2019), Li et al. (2019), Morgan (2019), Aghimien et al. (2020b), Hetemi et al. (2020), and Succar and Poirier (2020)
Collaboration (n = 14)	Oesterreich and Teuteberg (2016), Dallasega et al. (2018), Heusler and Kadija (2018), Papadonikolaki (2018), Woodhead et al. (2018), Koseoglu et al. (2019), Papadonikolaki et al. (2019), Singh (2019), Aghimien et al. (2020a), Aghimien et al. (2020b), Craveiroa et al. (2019), Darko et al. (2020), Hetemi et al. (2020), and Keskin et al. (2020)
Learning (n = 4)	Dallasega et al. (2018), de Soto et al. (2018), Chen (2019b), and Aghimien et al. (2020b)
Value (n = 9)	Dallasega et al. (2018), Maskuriy et al. (2019a), Craveiroa et al. (2019), Aghimien et al. (2020b), Darko et al. (2020), Greif et al. (2020), Hetemi et al. (2020), Pham et al. (2020), Tezel et al. (2020), and Winch and Cha (2020)
Lifecycle (n = 8)	Papadonikolaki (2018), Woodhead et al. (2018), Chen (2019a), Koseoglu et al. (2019), Aghimien et al. (2020b), Keskin et al. (2020), Newman et al. (2020), and Succar and Poirier (2020)
Choice of digital (n = 7)	Dallasega et al. (2018), Braun and Sydow (2019), Koseoglu et al. (2019), Aghimien et al. (2020a), Newman et al. (2020), Pan et al. (2020), and Pham et al. (2020)
Data (n = 3)	Woodhead et al. (2018), Braun and Sydow (2019), and Pham et al. (2020)

understanding of how it fosters stakeholder collaboration (Yang and Chou, 2019). It becomes apparent that strategic consideration should promote collaboration in a virtual environment, such as those apparent with the platforms for BIM tools (Koseoglu et al., 2019). The benefit is a synergistic working relationship among stakeholders (Dallasega et al., 2018) and greater project performance (Papadonikolaki, 2018; Papadonikolaki et al., 2019). In practice, the strategic consideration that promotes collaboration can be experienced as digital partnering among project organizations to share digital resources (Lavikka et al., 2017; Aghimien et al., 2020a). Furthermore, it could be a technology-enabled collaborative ecosystem (Aghimien et al., 2020a) where digital technologies coevolve across software, hardware, products, people, and process (Singh, 2019; Hetemi et al., 2020; Keskin et al., 2020). Therefore, the strategic consideration specifies how people and machine can be connected, especially in large-scale infrastructure projects (Keskin et al., 2020). This strategic consideration needs to be in place to guide the implementation of cobots (collaborative robots) to work with humans in construction environments (Darko et al., 2020).

Learning

Technology always does change, whereby the starting point is often discreet and the learning curve is never-ending (Buisman, 2018). Seemingly, new digital technologies are produced on an incremental basis that often results in subsequent model upgrades. This creates a need for continuous learning among digital technology implementers in construction, basically understanding the new features in upgraded digital technologies and applying them correctly (de Soto et al., 2018). Therefore, the strategic consideration for continuous digital learning is necessary and has been found to increase the understanding of the gaps and solutions to digital technology applications in design, construction, and operation phases (Chen, 2019b). The strategic consideration for continuous learning stipulates the feedback process, whereby lessons learnt from implemented digital technologies in construction become inputs for improving future digital technology design and development (Dallasega et al., 2018; Chen, 2019b). The implementation of 3D printing technology in the manufacturing sector is considered. Continuous learning among construction stakeholders has been found useful to adapt the technology in the construction sector (Chen, 2019b). Consequently, the technology is gradually becoming domain specialization in construction (Dallasega et al., 2018).

Value

It is important to identify the quantitative and qualitative benefits that could be derived from the implementation of digital technologies in construction (Darko et al., 2020). This corresponds to value capture and can be achieved by developing business cases that specify the value added by using digital technologies in construction (Winch and Cha, 2020). Therefore, strategic consideration for implementing digital technologies should incorporate business case development (Tezel et al., 2020; Winch and Cha, 2020). The business case of digital technologies reveals benefits and/or value added in the short and long terms. For digital technologies with a high initial cost, such as 3D printing, the business case should specify the value added in the long term (Craveiora, 2019). Such technologies are more likely to deliver higher value when used over a long period (Craveiroa et al., 2019). Similarly, the use of AI technologies can be costly in terms of money, time, and complexity; therefore, the business case should be developed to cover a long-term period (Darko et al., 2020). In sum, business case development capturing the value of digital technologies is a strategic way of justifying investment in digital technologies in construction in both the short and long terms (Greif et al., 2020; Hetemi et al., 2020).

Lifecycle

Increasingly, digital technologies such as the cloud technology that support lifecycle project implementation are being produced. Cloud technology is used for automating lifecycle tasks in construction (Keskin et al., 2020), such as lifecycle information exchange, as demonstrated in the work of Succar and Poirier (2020). Therefore, strategic consideration should envision and support the implementation of digital technologies over the project lifecycle. This ensures that the transformation impacts can be experienced over the built asset lifecycle (Koseoglu et al., 2019; Keskin et al., 2020). For instance, the BIM execution plan is an operational strategy for BIM implementation not just at the project design stage but throughout the project lifecycle. According to Papadonikolaki (2018), extending BIM implementation to the end of the built asset lifecycle through facility management has increased BIM implementation and impacts in the construction supply chain and many construction organizations The consequence, which can also be observed in IoT implementation, has helped construction organizations to adapt better to digital evolutions (Woodhead et al., 2018) that guarantee positive outcomes (Newman et al., 2020).

Choice of Digital

Implementing digital technologies should not be an arbitrary choice despite the amazing benefits of enhancing construction processes (Newman et al., 2020). There should be a deliberate attempt to identify and select the type of digital investment in construction (Dallasega et al., 2018; Newman et al., 2020). Therefore, a strategic consideration that guides the choice of digital investment is needed. Importantly, strategic consideration is needed to comprehend diverse digital tools and when they should be deployed (Newman et al., 2020). This is relevant to ensure that digital technologies are implemented only where efficiency of construction tasks can be achieved and vice versa (Newman et al., 2020). For instance, the potential of using robots to improve efficiency on construction sites is still shrouded in uncertainty (Pan et al., 2020) and this has increased the need to identify the digital technologies that are easier and less burdensome to implement (Dallasega et al., 2018). Particularly, in small organizations, digital technologies that are simple and familiar and better adaptable to the operation process should be a strategic choice (Pham et al., 2020). Project, time, size, and duration are additional factors that should be considered in determining the choice of digital technologies in construction (Koseoglu et al., 2019). Finally, an entire set of very diverse capabilities is needed for utilizing new technologies (Braun and Sydow, 2019; Aghimien et al., 2020a), and the availability of these capabilities should be strategically considered in the choice of digital investments in construction (Braun and Sydow, 2019).

Data

Enormous data are increasingly generated in the construction process (Woodhead et al., 2018). It is of strategic importance to consider making such data available (Buisman, 2018) from one technology to another (Pham et al., 2020), from a physical to a virtual world (Woodhead et al., 2018), and from one construction phase to another (Braun and Sydow, 2019). This increases the potential of data analytics in construction, which contributes to smart management and sound decision making (Woodhead et al., 2018; Pham et al., 2020). Data-centric strategic consideration is very relevant for implementing digital technologies such as drones, robots, and 3D printing to perform tasks on construction sites without human inputs (Woodhead et al., 2018). A strategic consideration that specifies the requirements of such technologies is necessary, for instance, to ensure that they are capable of concurrent copying of data streams to multiple destinations such as a database or analytics engine (Woodhead et al., 2018).

Enablers of Digital Transformation in Construction

Enablers facilitate successful/beneficial DT in construction. As shown in **Table 2** and **Figures 2**, **3**, the results of the open coding, axial coding, and selective produce the nine enablers of DT in construction, namely, digital champions, the attraction of digital, training opportunities, innovativeness, system support, and new forms of organization. Others are digital culture, legitimation, and research. They are described in this section, and the summary of the literature on the strategic considerations is presented in **Table 4**.

Digital Champions

The implementation of digital technologies in construction produces digital leaders who are known as digital champions (Morgan, 2019). Taking an example of BIM implementation, BIM champions are distinguished from adopters-only by emphasizing institutional outcomes beyond implementation-only (Azzouz and Papadonikolaki, 2020), such as digital knowledge networking (Azzouz and Papadonikolaki, 2020; Hetemi et al., 2020). Digital champions can be construction and project leaders who imbibe a strong commitment to implement digital technologies even when inconvenient (Chen, 2019a; Aghimien et al., 2020b). Such commitment can be exemplary for operation-level employees in construction (Berlak et al., 2020) and has been found to motivate them to become digital champions (Bonanomi et al., 2019). At the organization level, digital champions have been found to encourage the interorganizational application of digital technologies through digital partnerships (Aghimien et al., 2020b). Furthermore, digital champions facilitate DT at the institutional level, ensuring that the application of digital technologies by digital agents (users) conforms with professional institution rules and standards in the construction industry (Morgan, 2019).

Attraction of Digital

The use of digital technologies has become an attraction point that accelerates DT in construction due to the possibilities of performing tasks digitally. With digital technologies, the construction skill-base is digitally empowered (Craveiroa et al., 2019), and construction processes are transformed (de Soto et al., 2018). Studies have identified the emergence of new construction skills (e.g., construction informatics and block chaining) (Tezel et al., 2020), displacement of jobs such as traditional cost quantification (de Soto et al., 2018), and the evolution of new tasks such as sensor monitoring (Woodhead et al., 2018) as transformations that emerged following the use of digital technologies in construction. The enthusiasm for such transformations is greater among the young generation of construction employees who are keen to use new technologies and deploy new ways of working (Pham et al., 2020; Soman and

TABLE 4 | Summary of inductive literature on enablers of DT in construction.

Enablers	Sources
Digital champions (n = 8)	Woodhead et al. (2018), Chen (2019a), Bonanomi et al. (2019), Morgan (2019), Aghimien et al. (2020b), Azzouz and Papadonikolaki (2020), Berlak et al. (2020), and Hetemi et al. (2020)
Attraction of digital technologies (n = 17)	de Soto et al. (2018), Goulding et al. (2018), Heusler and Kadija (2018), Woodhead et al. (2018), Braun and Sydow (2019), Craveiroa et al. (2019), Koseoglu et al. (2019), Li et al. (2019), Papadonikolaki et al. (2019), Singh (2019), Hetemi et al. (2020), Newman et al. (2020), Pan et al. (2020), Pham et al. (2020), Tezel et al. (2020), and Winch and Cha (2020)
Training opportunities (n = 15)	Goulding et al. (2018), Woodhead et al. (2018), Maskuriy et al. (2019b), Koch et al. (2019), Koseoglu et al. (2019), Li et al. (2019), Singh (2019), Aghimien et al. (2020b), Darko et al. (2020), Greif et al. (2020), Hetemi et al. (2020), Newman et al. (2020), Pan et al. (2020), and Winch and Cha (2020)
Innovativeness (n = 12)	Goulding et al. (2018), Papadonikolaki (2018), Woodhead et al. (2018), Chen (2019b), Maskuriy et al. (2019b), Craveiroa et al. (2019), Singh (2019), Azzouz and Papadonikolaki (2020), Hetemi et al. (2020), Keskin et al. (2020), and Pan et al. (2020)
Third-party support (n = 11)	Aghimien et al. (2020a); Aghimien et al. (2020b); Berlak et al. (2020); Bonanomi et al. (2019); Braun and Sydow (2019); Chen (2019b); Newman et al. (2020); Pan et al. (2020); Tezel et al. (2020); and Woodhead et al. (2018)
New forms of organization (n = 15)	Oesterreich and Teuteberg (2016), Maskuriy et al. (2019b), Bonanomi et al. (2019), Braun and Sydow (2019), Koseoglu et al. (2019), Morgan (2019), Azzouz and Papadonikolaki (2020), Berlak et al. (2020), Darko et al. (2020), Greif et al. (2020), Hetemi et al. (2020), Newman et al. (2020), and Pham et al. (2020)
Culture inclusion (n = 10)	Dallasega et al. (2018), Woodhead et al. (2018), Maskuriy et al. (2019), Koseoglu et al. (2019), Azzouz and Papadonikolaki (2020), Berlak et al. (2020), Hetemi et al. (2020), Newman et al. (2020), Pan et al. (2020), and Tezel et al. (2020)
External legitimation (n = 8)	Papadonikolaki (2018), Chen (2019a), Koseoglu et al. (2019), Li et al. (2019), Morgan (2019), Papadonikolaki et al. (2019), Hetemi et al. (2020), and Tezel et al. (2020)
Research potential (n = 6)	Oesterreich and Teuteberg (2016), Dallasega et al. (2018), Chen (2019b), Singh (2019), Pan et al. (2020), and Tezel et al. (2020)

Whyte, 2020). They strengthen their technical skills and soft skills such as communication (Braun and Sydow, 2019; Papadonikolaki et al., 2019; Winch and Cha, 2020), which promotes them from digital talents to digital agents (Goulding et al., 2018; Azzouz and Papadonikolaki, 2020). Encouraging the young generation to use digital technologies to perform construction tasks is key to DT in construction (Koseoglu et al., 2019). Another key aspect is that the construction sector is an intellectual space where digital talents are challenged and cultivated with creative professional opportunities that lead to DT progress (Singh, 2019; Pan et al., 2020). This is accentuated by the limited knowledge of construction in the IT industry, which creates a digital opportunity for construction professionals and practitioners (Woodhead et al., 2018).

Training Opportunities

The rise of digital technologies invokes an educative agenda (Li et al., 2019), manifested in the form of continuous digital training (Aghimien et al., 2020b; Hetemi et al., 2020). The training has increased digital knowledge, skills, and capabilities in construction (Goulding et al., 2018; Li et al., 2019; Aghimien et al., 2020b). Intraorganizational (including project organization) digital training (e.g., facilitated workshops and meetings) is used to shorten the digital learning curve, particularly for young people in construction (Koseoglu et al., 2019; Aghimien et al., 2020b). However, such pieces of training require outsourced specialists (Koch et al., 2019), which is time consuming and expensive in BIM training (Newman et al., 2020). Also, institutionalized training that enables an organic development of digital innovation industry wide is rising (Maskuriy et al., 2019b; Azzouz and Papadonikolaki, 2020). For example, the degree apprenticeship model of undergraduate education has increasingly been used to enhance students' digital capabilities and graduates in the United Kingdom construction industry (Woodhead et al., 2018). This model underscores the importance of higher education in the journey toward DT in the construction industry. Interindustry digital training is increasing in the construction industry (Goulding et al., 2018; Darko et al., 2020) which, for instance, has been useful to harvest prefabrication and robotics development skills from manufacturing and engineering sectors, respectively (Pan et al., 2020; Singh, 2019).

Innovativeness

The increasing use of digital technologies has created a fertile environment for construction innovation (Craveiroa et al., 2019; Pan et al., 2020). The commonest one is the use of digital technologies that are primarily domiciled in the manufacturing sector. It has led to the cultivation of an interdisciplinary digital innovation environment that allows construction practices to interface with practices in other sectors (Chen, 2019b). It has also increased technology transfer between the construction and other sectors (Goulding et al., 2018; Singh, 2019). Interestingly, digitally savvy construction clients have capitalized on the interface created (Azzouz and Papadonikolaki, 2020) to learn from other sectors and demand similar digital technology applications in their projects (Woodhead et al., 2018). It now represents how construction clients bring innovation to their projects and, in the process, influencing those involved to use digital technologies in the project delivery process (Hetemi et al., 2020). However, innovation can either be positive or negative. On a positive note, the transformative impact of these innovations increases the implementation of digital technologies. On a negative note, an aggressive could trigger an industry-wide attitude against the use of digital technologies and impair innovation in the process (Koseoglu et al., 2019).

Third-Party System Support

The availability of a third-party (system) supports the successful implementation of digital technologies in construction (Aghimien et al., 2020b). Sepasgozar and Loosemore (2017) identified visionaries, innovators, followers, and conservative categories of the interplay that exist between the stakeholders who manufacture digital technologies (or vendors) and the customers who use them in construction. Manufactures who are visionaries provide installation supports (either online or physically) for digital technologies procured for construction purposes (Berlak et al., 2020). Such supports from Autodesk solutions have increased the usage of digital technologies in construction (Newman et al., 2020). Recently, system support has gradually extended to benchmarking the impact of digital technologies on construction performance bottomlines (e.g., productivity and competitiveness) (Berlak et al., 2020). This has increased cocreation between innovative (or innovators) construction stakeholders and manufacturers such as Autodesk to produce customized digital technologies (Woodhead et al., 2018) and transforming existing digital capabilities in the process (Braun and Sydow, 2019). For robotic design and implementation on construction sites, cocreation between construction stakeholders and manufacturers has helped develop real world-class proofs-of-concept (Pan et al., 2020) by the pragmatists (Sepasgozar and Loosemore, 2017). Another aspect of system support is when construction organizations engage in digital partnership with IT domain organizations (Aghimien et al., 2020a). As demonstrated in a BIM implementation study (Braun and Sydow, 2019), it is conservatively engaging in digital partnerships to avail the digital resources and capabilities that were not present but the key to successful BIM implementation (Bonanomi et al., 2019; Aghimien et al., 2020a).

New Forms of Organization and Restructuring

New forms of organization encompassing project and organizational relationships, roles and responsibilities, and organizational structure are necessary to derive the full benefits of digital technologies and the transformational impacts in construction (Bonanomi et al., 2019; Darko et al., 2020). Less departmentalized structures allow employees to easily distribute digital knowledge in construction organizations (Bonanomi et al., 2019; Hetemi et al., 2020). The size of construction organizations is important. In both large and small organizations, it is essential to clarify the ease of digital technology diffusion in either type (Morgan, 2019; Newman et al., 2020). Role flexibility that permits construction professionals to engage other responsibilities beyond their primary domain enhances DT, especially in large organizations (Bonanomi et al., 2019; Azzouz and Papadonikolaki, 2020). It allows practitioners to have more room to draw on individual, organizational, and institutional resources to innovate freely (Morgan, 2019). Besides, the flexibility ensures that existing informal roles and relationships are not destroyed but properly aligned with new ones (Bonanomi et al., 2019). New roles such as Chief Digital Office (CDO) (and departments) are increasingly created to deliver the transformation impacts of digital technologies, particularly BIM (Maskuriy et al., 2019b; Braun and Sydow, 2019; Koseoglu et al., 2019; Azzouz and Papadonikolaki, 2020).

Digital Culture

Digital technologies can be a source of disruption to existing operational culture in construction (Newman et al., 2020). To avoid shocks, digital culture needs to be embedded in the sociocultural expectations across projects, organizations, and institutions in the construction industry (Hetemi et al., 2020). Many studies have shown that BIM implementation is easier when the implementers' values, attitudes, and internal practices are receptive to the digital culture [e.g., Dallasega et al. (2018); Koseoglu et al. (2019); Azzouz and Papadonikolaki (2020)]. Additionally, such receptive values, attitudes, and internal practices prevent employee resistance to BIM implementation (Koseoglu et al., 2019; Newman et al., 2020). Accepting digital technologies is increasingly becoming a cultural necessity in construction (Newman et al., 2020), capable of speeding up DT in construction (Maskuriy et al., 2019b).

External Legitimation

Many digital technologies in construction are not solutions in and of themselves, which is apparent in blockchain, but becomes a better solution when integrated with the internet or IoT (Li et al., 2019). Legitimizing such an integration, both legally and ethically (Li et al., 2019), prescribes how to properly implement such digital technologies in an integrated manner (Papadonikolaki, 2018). In practice, construction organizations are responsible for obtaining such legitimacy (Hetemi et al., 2020) from the government (Morgan, 2019), whose role has become dominant (Hetemi et al., 2020). The government is primarily responsible for issuing directives and national initiatives that promote the integration of digital services and those that promote the interoperability of digital technologies (Koseoglu et al., 2019; Li et al., 2019). The Norway BIM manual and United Kingdom BIM level 2 mandate are some of the directives for controlling BIM instrumentality in the public domain. Deriving from the role of the government, professional institutions and professional bodies have also issuing initiatives (e.g., precontract BIM execution plan) for quasicontractual digital collaboration (Papadonikolaki, 2018; Papadonikolaki et al., 2019) and generating a common platform for BIM use among multidisciplinary actors (Morgan, 2019). Such external legitimation, either by the government or professional institutions, has become the guideline for implementing digital technologies in construction; an example is the use of BIM in public tendering in Spain (Hetemi et al., 2020). On the downside, the role of government in legitimizing digital technologies is focused mainly on BIM in the United Kingdom, the United States, China, and European countries. In contrast, other digital technologies in other countries are still left out. Regardless, a study on blockchain application in construction speculated that external legitimation through the government's role would continue with increasing attention on digital technologies in construction (Chen, 2019a; Tezel et al., 2020).

TABLE 5 | Summary of inductive literature on barriers to DT in construction.

Threats	Sources
Complex data processing (n = 11)	Heusler and Kadija (2018), Chen (2019a), Chen (2019b), Koch et al. (2019), Koseoglu et al. (2019), Li et al. (2019), Maskuriy et al. (2019b), Aghimien et al. (2020a), Keskin et al. (2020), Pham et al. (2020), and Tezel et al. (2020)
Data access and ownership (n = 8)	Woodhead et al. (2018), Chen (2019), Koch et al. (2019), Koseoglu et al. (2019), Li et al. (2019), Singh (2019), Aghimien et al. (2020a), and Berlak et al. (2020)
Lack of system integration (n = 13)	Oesterreich and Teuteberg (2016), Woodhead et al. (2018), Chen (2019a), Chen (2019b), Braun and Sydow (2019), Koch et al. (2019), Koseoglu et al. (2019), Darko et al. (2020), Greif et al. (2020), Hetemi et al. (2020), Keskin et al. (2020), Succar and Poirier (2020), and Zabidin et al. (2020)
ROI uncertainty (n = 12)	de Soto et al. (2018), Woodhead et al. (2018), Chen (2019), Koseoglu et al. (2019), Li et al. (2019), Aghimien et al. (2020a), Berlak et al. (2020), Greif et al. (2020), Newman et al. (2020), Oesterreich and Teuteberg (2016), Tezel et al. (2020), and Winch and Cha (2020)
Low standardization (n = 8)	Woodhead et al. (2018), Chen (2019a), Craveiroa et al. (2019), Koch et al. (2019), Morgan (2019), Papadonikolaki et al. (2019), Succar and Poirier (2020), and Tezel et al. (2020)
Lack of owner buy-in (n = 10)	Dallasega et al. (2018), Woodhead et al. (2018), , Koch et al. (2019), Koseoglu et al. (2019), Aghimien et al. (2020a), Berlak et al. (2020), Hetemi et al. (2020), Keskin et al. (2020), Newman et al. (2020), and Winch and Cha (2020)
Displacement of old workers (n = 5)	Woodhead et al. (2018), Braun and Sydow (2019), Koseoglu et al. (2019), Maskuriy et al. (2019), and Pan et al. (2020)
Existence of old business models (n = 6)	Goulding et al. (2018), Woodhead et al. (2018), Koseoglu et al. (2019), Singh (2019), Keskin et al. (2020), and Tezel et al. (2020)
Digital divide (n = 9)	Goulding et al. (2018), Koseoglu and Nurtan-Gunes (2018), Papadonikolaki (2018), Bonanomi et al. (2019), Morgan (2019), Berlak et al. (2020), Newman et al. (2020), Pan et al. (2020), and Tezel et al. (2020)
Risk of system attacks (n = 5)	Woodhead et al. (2018), Chen (2019a), Maskuriy et al. (2019a), Morgan (2019), and Tezel et al. (2020)

Research

The prospects of digital technologies such as robotization of construction sites, but which are yet to be practicable, have become the heart of funded research and development in construction (Pan et al., 2020). Practical implementation of technologies such as 3D printing has mostly been limited to field tests (Dallasega et al., 2018). To move forward, academic and practitioner research and development stands as a key enabler to demonstrate the practicability of digital technologies more widely (Chen, 2019b; Pan et al., 2020). While aiming for wider dissemination, it is better to start exploratorily through limited trials that academic researchers can present to industry stakeholders before embarking on practical implementation (Singh, 2019). Academic research is critical; for instance, academic researchers can employ theories that interface multiple disciplines (e.g., computer science) for theoretical exploration of digital technologies and prescribe those that are relevant to construction tasks (Singh, 2019; Tezel et al., 2020). This has created a growing ecosystem of research mavericks such as Dr. Amos Darko (Darko et al., 2020), who continually focus on expanding the research potential of digital technologies in construction (Chen, 2019b; Singh, 2019).

Barriers to Digital Transformation in Construction

Barriers suppress DT in construction. As shown in **Table 2** and **Figures 2**, **3**, the results of the open coding, axial coding, and selective coding produce ten barriers of DT in construction, namely, complex data processing, data access and ownership, system integration, return on investment uncertainty, and low standardization. Others are lack of owner buy-in, displacement of older workers, digital divide, and risk of system attacks. They are described in this section, and the summary of the literature on the strategic considerations is presented in **Table 5**.

Complex Data Processing

Digital technologies used in project design, construction and operation, and management operations in construction organizations generate a large amount of (semantic and geometric) data that are complex to process and analyze (Keskin et al., 2020). It is more complex when data need to be transferred from one digital technology to another (e.g., a sensor on site to an office server) (Buisman, 2018). The use of AI and ML techniques has helped process and analyze complex construction data but not without shortcomings. Real-time data processing and analytics may not be possible given the lengthy data preparation involved before the techniques can be used to obtain valid results (Heusler and Kadija, 2018; Maskuriy et al., 2019b; Chen, 2019b). One that is apparent with BIM data is the complexity of processing and analyzing construction data that are derived from different trades (Keskin et al., 2020). From studies, this prevents attempts at making sense of BIM data from constructors and facility managers involved in a large airport project (Koch et al., 2019; Koseoglu et al., 2019). This is a threat to DT in construction in the form of isolated digital solutions instead of embedding digital solutions from different disciplines (Koseoglu et al., 2019). Concerning the blockchain, the public blockchain can only process small amounts of data, limited to few transactions per second (Tezel et al., 2020), which undermines its integration with smart cities and digital twins (Chen, 2019a; Li et al., 2019). However, data processing may not be complex in small organizations that mostly generate small construction data (Pham et al., 2020).

Data Access and Ownership

Data produced in construction processes are still being treated as confidential as many construction projects and organizations struggle to achieve open-data sharing (Aghimien et al., 2020a). It creates legal issues (Maskuriy et al., 2019a) that are neither tested nor precedented (Li et al., 2019). For instance, data ownership and rights to use data are often tied together to the detriment of data sharing/access in construction (Chen, 2019a). Data owners are overly about privacy protection (Chen, 2019a), and they treat data independently across project delivery (e.g., planning data vs. execution data) (Koch et al., 2019; Berlak et al., 2020). With multiple project phases or multiple departments involved, it leads to independent data management where data are barely shared Chen (2019a). Concerning recent BIM platforms (e.g., BIM 360), they allow data access across project phases (Koseoglu et al., 2019), but legal and interoperability issues remain to be fully addressed (Koch et al., 2019).

System Integration

Lack of system integration is the nonalignment or incompatibility of implemented digital technologies in construction (Braun and Sydow, 2019) and lack of an integrated layer of hardware, software, information flows, and connectivity (Woodhead et al., 2018). As commonly experienced in BIM implementation, the problem is escalated when different trades use incompatible software packages that are not integrated sufficiently (or interoperable) (Braun and Sydow, 2019; Koch et al., 2019). Also, deriving from the interoperability problem is the limited end-to-end integration of the new generation of digital technologies (e.g., IoT, blockchains, cloud platform, AI, and big data) across the construction value chain (Chen, 2019a). It restricts digital technologies to a specific application, focuses on a singular problem or one use-case (Woodhead et al., 2018), such as an enterprise management system (EMS) that records the wage rate of construction workers but not linked to their productivity on-site (Chen, 2019b). To avert this problem, the practice has been to combine many point solutions that rarely accept integrative use of data (Woodhead et al., 2018; Chen, 2019b), thereby leading to silo solutions (Greif et al., 2020). According to Zabidin et al. (2020), nonintegration leads to using digital technologies independently of one another, which decelerates DT in construction. For instance, a lack of integration between BIM and IoT prevents the cyber-physical potential and prevents a bidirectional information exchange between the physical and virtual environments (Zabidin et al., 2020).

Low Standardization

Compounding the lack of system integration is the lack of standards (or standardization) to guide the integration of various digital technologies in construction (Chen, 2019a). This reduces the choice of digital technologies that are installed in the technology ecosystem of construction (Woodhead et al., 2018; Tezel et al., 2020). This problem is more cumbersome in the building operation phase due to a lack of standards to guide the integration of digital technologies (Koch et al., 2019). A plethora of standard documents, such as the ISO suit of standards (Morgan, 2019; Succar and Poirier, 2020), has been released to standardize the integration of digital technologies in construction (Woodhead et al., 2018; Succar and Poirier, 2020). However, it has resulted in overstandardization, making it difficult to determine what to standardize (or not) given the influx of digital technologies implemented in construction (Succar and Poirier, 2020). Also, the ISO standards do not provide adequate guidelines for integrating digital technologies that overlap sectors (e.g., 3D printing application in the manufacturing sector) (Craveiroa et al., 2019; Succar and Poirier, 2020), which is perhaps due to the gap between the standardization approaches in the product-oriented manufacturing industry and the process-oriented construction industry (Succar and Poirier, 2020). In practice, the lack of standards for integrating digital technologies that overlap sectors frustrates smart-city development (Chen, 2019a).

Return on Investment Uncertainty

Digital technologies in construction often incur high initial costs (Newman et al., 2020), and this invokes a notion of quick return on digital investment (ROI) among adopters (Woodhead et al., 2018; Berlak et al., 2020). In particular, the owner organizations in construction are fixated on the notion of benefits realization when investing in digital technologies (Winch and Cha, 2020). According to Woodhead et al. (2018), this notion fuels hesitation because of the uncertainty that often surrounds the benefits of digital technologies in construction (Oesterreich and Teuteberg, 2016). The notion encourages “future-safe” rather than aggressive investment in digital technologies (Woodhead et al., 2018; Greif et al., 2020). Consequently, the fear of loss of digital investment is created (Woodhead et al., 2018; Aghimien et al., 2020a) and reinforced by a low-profit margin in construction (Newman et al., 2020). Hesitation to invest in digital technologies is greater in small companies due to fewer incentives to recoup investment (Tezel et al., 2020). Meanwhile, it is not all gloom as assuredness in the ROI of digital investments can be achieved. From an analysis of the cost of robots, repetitive application robots in complex projects only are more economically competitive (de Soto et al., 2018). Also, assuredness in the ROI on digital investments increases where a small amount of data is generated and analyzed (Chen, 2019a). Large amount of data poses difficulties in the analytics and increases the operational costs (Chen, 2019a).

Lack of Owner Buy-In

According to Winch and Cha, 2020, the objective of implementing digital technology in construction should conform with owners’ requirements and expectations of project delivery and organization performance. This guarantees not only owner buy-in in digital technologies (Hetemi et al., 2020; Keskin et al., 2020) but also the changes that may occur to the owner project and organization due to the implementation of digital technologies (Aghimien et al., 2020a; Berlak et al., 2020). For instance, digital capabilities in the owner organization need to be functional to support digital technology implementation (Newman et al., 2020; Tezel et al., 2020). However, the lack of owner buy-in in digital technologies is still pervasive in construction and their inability to adapt to the emerging changes (Koch et al., 2019). Lack of owner buy-in in digital technologies manifests through their add-on mentality of digital technologies (Papadonikolaki et al., 2019) and emphasises the partial implementation of digital technologies (Dallasega et al., 2018; Hetemi et al., 2020). It should be noted that lack of owners’ buy-in does not mean an absence of digital technology implementation in owners' projects or organizations. The issue is that the use of digital technologies in owner projects (Koseoglu et al., 2019; Winch and Cha, 2020) has not been optimal due to the lack of owners' buy-in (Berlak et al., 2020).

Displacement of Old Workers

Owing to the dynamic development of technology, the implementation of digital technologies in construction has introduced digital capabilities that are opaque but, more worryingly, tied mainly to young people (e.g., construction informatics) (Braun and Sydow, 2019; Koseoglu et al., 2019). Contrary to the knowledge management principle (Grant, 2002), this happenstance continues to displace older people who have experiential domain knowledge that fosters DT when appropriately combined with the digital capabilities of young people in construction (Woodhead et al., 2018). In parallel, part of the problem is the threat of displacing traditional roles (e.g., material inventory) that are commonly handled by older people on construction sites with digital technologies (e.g., robots) (Woodhead et al., 2018; Pan et al., 2020). This continues to derail the experiential contribution of older people in construction. The older people, especially those occupying strategic positions in project organizations, have been found to manifest their frustrations by demonstrating opposition attitude to digital technology use in construction projects (Koseoglu et al., 2019). The characterization of aging to mean lack of skill (Pan et al., 2020) without an institutionalized age management approach to identify digital capabilities among older people is commonplace in construction and has set back DT efforts (Maskuriy et al., 2019b).

Old Business Models

The implementation of digital technologies is supposed to lead to innovative business models (where business and IT are integrated) that transform the digital construction production process (Koseoglu et al., 2019; Keskin et al., 2020). This means the elimination of physical construction (Singh, 2019) in favor of service-only construction (Keskin et al., 2020), such as IoT-enabled selling of "buildings as a service" or self-organizing trades using blockchain (Woodhead et al., 2018). However, it is impossible, thereby retaining the existing (old) business models in construction (Tezel et al., 2020). Part of the problem is the lack of precedence (or use-cases) of the innovative business models in construction (Singh, 2019; Tezel et al., 2020). This condemns the innovative business models as a subjective proposition (Goulding et al., 2018). Trade-off of the existing business models remains a conflicting issue, especially for the incumbent construction organizations (Verhoef et al., 2019).

Digital Divide

The digital divide manifests in large and often incumbent construction organizations having more resources and influence to exert greater external changes and internal practices through the application of digital technologies (Morgan, 2019). Small organizations have the advantage of adapting faster to changes resulting from digital technology implementation (Morgan, 2019) but fewer resources and influence (Goulding et al., 2018; Papadonikolaki, 2018). As a result of the digital divide, blockchain's traceability and transparency functions are easily translated to business models in large construction organizations (Tezel et al., 2020). The digital divide in construction mainly favors/accentuates digital technology applications in large organizations. This automatically undermines DT in construction because the more populated small organizations in construction are left out (Berlak et al., 2020; Newman et al., 2020). Furthermore, with the dependence between large and small organizations in the supply chain (Newman et al., 2020), an inequivalent implementation of digital technologies reduces DT in construction (Craveiroa et al., 2019).

System Attacks

The increasing use of digital technologies elevates the risk of system attacks in construction (Maskuriy et al., 2019a). For instance, BIM tools are widely used digital technologies in construction, but very little has been done to secure BIM data (Maskuriy et al., 2019a). Data security in private blockchains is still prone to unsolicited data manipulations when applied in construction (Tezel et al., 2020). The study of smart city development in China has shown that data and system security can be very difficult due to persistent leakage in many digital technologies (Chen, 2019a). The strong potential of data and security breach (Koseoglu et al., 2019; Morgan, 2019) reduces client and user trust and confidence in the digital process in construction (Koseoglu et al., 2019).

Construction Activity Fields and Their Digital Transformation

The results of inductive content analysis produce six construction activity fields and their digital transformation, namely, concurrent designing and printing, construction process integration, interfirm relations, automated payment systems, digital construction, and information exchange. These provide insights into digital transformation in specific construction activity fields. Digital technology implementation can, therefore, be focused on the activity fields for increased digital transformation in construction. They are described in this section and illustrated in **Figure 6**.

Concurrent Designing (and Printing)

Architectural and engineering designing is a construction activity that is actively undergoing digital transformation in the construction sector. The use of digital technologies has led to a shift from symbolic 2D drawings (plans, sections, and elevations) to the creation of objects that could be modeled, visualized, exchanged, and analyzed within a 3D space. These characteristics enable the digital transformation of architectural and engineering designs in construction. As demonstrated in Craveiroa et al. (2019), the 3D printing technology (using the extrusion or binder jetting processes) enables the concurrent designing and construction of concrete and other polymetric construction elements. Also, Heusler and Kadija (2018) employed Artificial Intelligence to propose a semiautomatic and generative

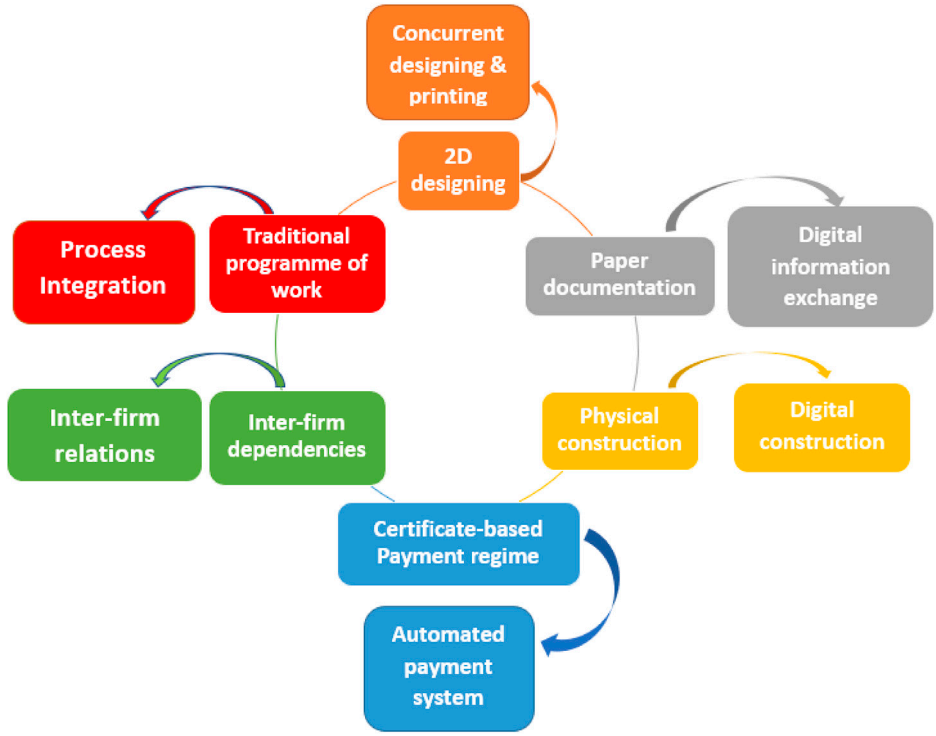

FIGURE 6 | Construction activity fields and their digital transformation.

design of façade in buildings that are both rule and intuition based.

Construction Process Integration

The implementation of digital technologies, especially BIM, in construction project delivery has integrated construction processes, comprising the people, technology, and processes. Regarding the people, BIM implementation promotes a "bind" that may manifest in similar pressures and logics experienced among the actors in an organization (Hetemi et al., 2020). Also, BIM implementation leads to streamlining construction technology ecosystem uses that increase connectivity among project parties (Keskin et al., 2020). Therefore, BIM implementation merges the intraorganizational silos in the construction process and speeds up project delivery (Koseoglu et al., 2019; Azzouz and Papadonikolaki, 2020).

Interfirm Relations

Implementing BIM for construction project delivery has progressed interfirm dependencies toward interfirm relations in construction. Traditionally, mutual relations that exist between the organizations in the construction supply chain create dense interfirm dependencies. However, concerning digital information sharing, interfirm relations imbibe a network view of innovation, which manifests conditionally. As found in the work of Papadonikolaki (2018), BIM implementation that is internally motivated (e.g., increase the quality of service) leads to more collaborative and flexible relations with other BIM implementers. Otherwise, an externally motivated BIM implementation (e.g., gain market reputation) leads to competition that prevents smooth interfirm relations (Papadonikolaki, 2018). Furthermore, BIM implementers that share similar motivations produce more consistent project outcomes (Papadonikolaki, 2018). Interfirm relations exemplify a seamless digital technology organization to create transformational impacts in the construction supply chain (Morgan, 2019).

Automated Payment System

Effecting payments to vendors and linking them to contracts is also a construction activity experiencing digital transformation in the construction sector. Although blockchain (or Distributed Ledger Technology (DLT)) is still being experimented with in many instances, it is almost generally accepted technology for automating payments and contracts in construction (Tezel et al., 2020). Li et al. (2019) introduced the "Project Bank Accounts" (PBA) that was initiated in the United Kingdom as an electronic bank account set by the client (and the main contractor) to ring-fence funds for different contractors by putting the funds into a trust. Once a contractual obligation is completed, payments are automatically made by the clients directly and simultaneously to the main contractor and vendors associated with the PBA (Tezel et al., 2020). Similarly, smart contracts can embed funds into a contract to protect contractors and vendors from insolvency and could effect payments upon automation.

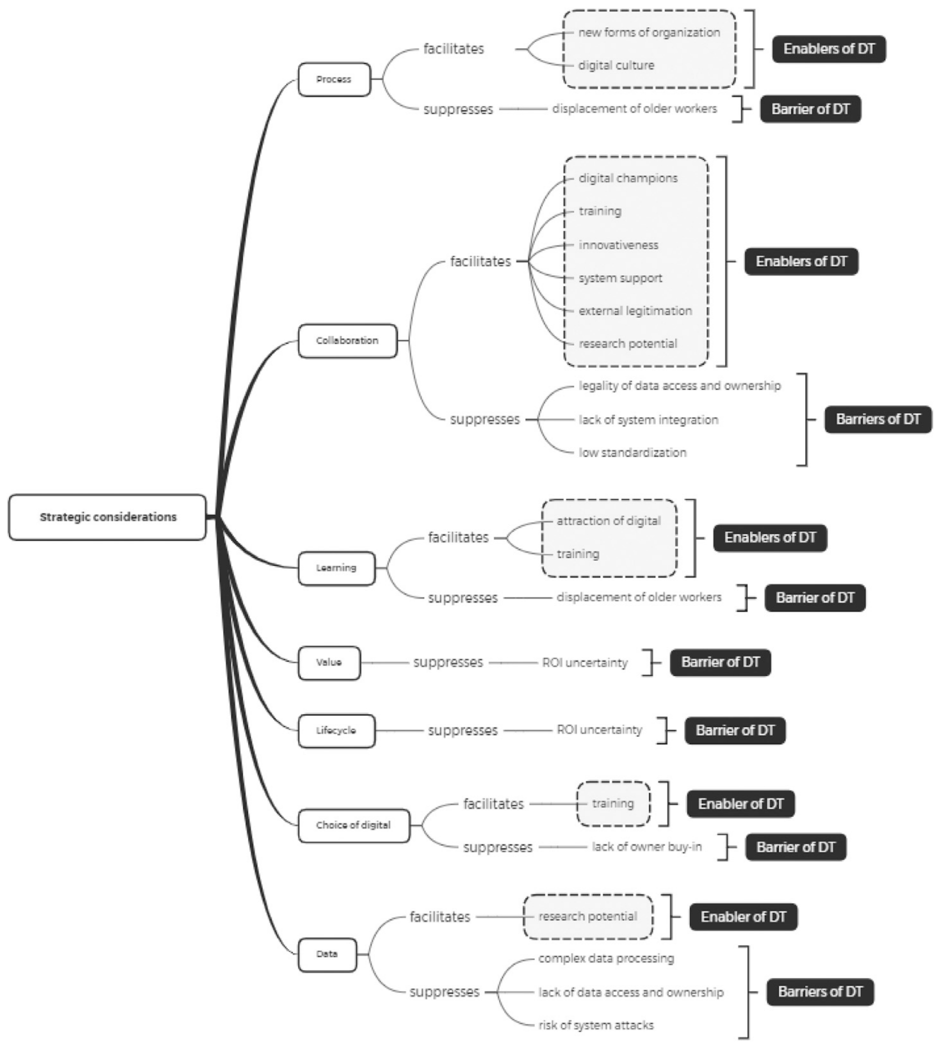

FIGURE 7 | Illustration of DT guideline in construction.

Digital Construction

The automation of excavation, movement of Earth, erection of forms or structures, purchase of materials and equipment, and other physical construction activities are increasingly implemented using digital technologies. For instance, robots have been implemented for residential wall construction (Berlak et al., 2020). Research has shown that robots increase productivity in concrete wall construction through efficient cost and time completion (de Soto et al., 2018). Another study reveals that BIM enhances project organization and controlling (Koseoglu and Nurtan-Gunes, 2018). Integrated teams using the BIM digital environment can respond immediately to project demands (Berlak et al., 2020). Therefore, BIM provides a digital construction management approach for construction managers (Koseoglu and Nurtan-Gunes, 2018). Furthermore, Greif et al. (2020) reveal the application of digital twins for automating construction site logistics. The study demonstrated the transformation of bulk silos for material storage through the application of digital twins.

Information Exchange

Digital technologies such as sensors used in construction project delivery generate data, which activates data/information exchange among integrated project team members. There is a significant loss of useful project information with a lack of a platform for information exchange or incompatible information exchange platforms (Koch et al., 2019). Increasingly, information exchange frameworks such as the "Lifecycle Information Transformation and Exchange (LITE)" framework is used for defining, managing, and integrating project and asset lifecycle information (Succar and Poirier, 2020). The LITE framework demonstrates the transformations possible with information exchange in construction. These include information flows from physical to digital assets, between small and large assets, and between assets within and beyond construction domains.

Other possible transformations are information exchange at different scales, such as single information exchange activity or a set of activities, information exchange in a project delivery phase or complete project delivery phases, or the whole asset lifecycle.

DISCUSSION

This review reveals the contributions that research has made toward an understanding of DT in construction. The inductive framework also highlights DT in construction as a process where the implementation of digital technologies creates transformation effects that trigger strategic considerations for putting in place the enablers that facilitate transformation effects and suppressing the barriers to it. Therefore, using a diagrammatic illustration (**Figure 7**), the strategic considerations for facilitating specific enablers and suppressing specific barriers to transformation effects in construction were presented. Furthermore, they are described in the following section to serve as DT guideline for the implementers of digital technologies in construction. In practice, it is expected that the guideline will help construction stakeholders to respond and adapt to DT in construction. Acknowledging that the DT guideline should be domain sensitive (Korachi and Bounabat, 2020), the previous studies on how to use DT guidelines in the IT, automation, financial services, and media sectors (Chanias and Hess, 2016; Chanias, 2017) were sector specific and did not specify guidelines for DT in the construction sector as suggested in the following.

Process. This strategic consideration facilitates two enablers of DT in construction, namely, *new forms of organization and digital culture*. Both the enablers relate to internal processes that foster (or hinder) organization objectives (including project organization). Among incumbent construction organizations, particularly the small ones, the diffusion of digital technologies is important to ensure that all internal members are involved in the implementation (Shibeika and Harty, 2015). This strategic consideration emphasizes the process approach to diffuse digital technologies, such as whether a digital technology should be trialed among a segment of people in an organization before extending it to other segments in the organization. Similarly, the strategic consideration emphasizes on a process-centric approach to embedding the digital culture that shapes the implementation of digital technologies among internal members in construction organizations. Furthermore, this strategic consideration suppresses only a barrier of DT in construction, namely, *displacement of older workers*. Specifying a process for identifying digital capabilities corresponding to age reduces the tendency to regard older workers as digitally naive in construction.

Collaboration. This strategic consideration facilitates six enablers and suppresses three barriers of DT in construction. Therefore, it is considered the most influential strategic consideration in this study. The six enablers are *digital champions, training, innovativeness*, and *systems support*. Others are *legitimation* and *research*. Digital champions are often in leadership positions and strongly motivated to help others understand the benefits and implementation of digital technologies (Grand Union Holding Group, 2020). This strategic consideration emphasizes the collaborative use of digital technologies among professionals, projects, and organizations, allowing digital champions to have greater influence. Both training and innovativeness enablers reiterate how the transformation effects of digital technology implementation overlap construction and other sectors such as the manufacturing sector. To this end, the emphasis on collaboration helps to bridge the gaps in digital technology implementation between the construction and other sectors. Regarding system support, it emphasizes after-sales support from product manufacturers and can extend to cocreation between manufacturers and product users in construction with appropriate collaboration strategies. Cocreation leads to the production of customized digital technologies in construction (Woodhead et al., 2018). Both legitimation and research enablers reiterate the construction stakeholders, including government and professional entities, who work together to ensure the integrated functioning of digital technologies. Strategic collaboration among these stakeholders ensures that beneficial DT is achieved in construction (Ezeokoli et al., 2016).

Furthermore, the three barriers are *data access and ownership, lack of system integration*, and *low standardization*. Regarding the legality of data access and ownership, the strategic considerations that promote collaborative use of digital technologies foster joint ownership of data and prevent users from independent data management (Pauwels et al., 2017) with significant legal implications (Fan et al., 2018). Also, regarding the lack of system integration, increasing digitization through a technology-enabled collaborative ecosystem reduces software incompatibility and point solutions in construction (Woodhead et al., 2018). Consequently, it increases the standardization of digital technologies and ease of implementing them in construction.

Learning. This strategic consideration facilitates two enablers of DT in construction, namely, the *attraction of digital* and *training*. Regarding the attraction of digital, the strategic consideration specifying model updates and upgrades creates opportunities to learn new things from the implementation of digital technologies. Also, it is a key attraction for young construction employees (Soman and Whyte, 2020). Also, regarding training, model updates and upgrades raise the need for digital training in construction. Meanwhile, this strategic consideration suppresses only a barrier to DT in construction, namely, *displacement of older workers.* The strategy that promotes inclusive digital training helps older workers increase their digital capabilities and obtain their inputs in digital learning.

Value. This strategic consideration suppresses only a barrier to DT in construction, namely, *ROI uncertainty*. It emphasizes the development of the business case for digital technologies, which in the case of BIM helps identify the benefits derivable, thereby removing the fears of loss of digital investment (Reddy, 2011; Raji et al., 2020).

Lifecycle. Like the *value* strategic consideration, this one also suppresses only the *DT's ROI uncertainty barrier* in construction. This strategic consideration overviews digital technologies as a long-term investment that extends over the project and organization lifecycle. This consideration quells the notion of quick ROI on digital investment in construction.

Choice of Digital. This strategic consideration facilitates an enabler of DT in construction, namely, *training.* It emphasizes choosing the digital technologies that can be easily implemented, which shortens the digital learning curve for the implementers in construction. Also, this strategic consideration suppresses a barrier to DT in construction, namely, *lack of owner buy-in.* The strategic consideration emphasizes aligning the choice of digital technologies to the objectives of project owners to serve as motivation to increase their investment in digital.

Data. This strategic consideration facilitates an enabler of DT in construction, namely, *research.* The emphasis is to make data from digital technologies available when implemented, and this increases the potential for further digital research in construction. Furthermore, this strategic consideration suppresses three enablers of DT in construction, namely, *complex data processing, data access and ownership*, and *risk of system attacks*. Regarding data processing and data access and ownership, this strategic consideration emphasizes making data available across platforms and project phases to ease data analytics and decision making and enhance data sharing and data dependency. Also, making data available should encompass data breach and security measures for preventing system attacks (Chong and Diamantopoulos, 2020).

This study identified that the implementation of digital technologies divided into digital data, automation system, digital access, and connectivity components had increased the potential of digital transformation in construction. The existing knowledge of digital transformation in other sectors such as IS and business economics does not provide an understanding of digital transformation in construction. However, with increasing literature on the implementation of digital technologies, this study took stock of the knowledge through an inductive literature review to provide an understanding of digital transformation in construction. Following the inductive review, the inductive framework that was developed highlights digital transformation in construction as a process where the implementation of digital technologies creates transformation effects that trigger strategic considerations for putting in place the enablers that facilitate transformation effects and suppressing the barriers to it. Subsequently, the variables of strategic considerations, enablers, and barriers identified from the review were described. Finally, the strategic considerations for facilitating specific enablers and suppressing specific barriers were discussed and presented as digital transformation guidelines in construction using an illustration (**Figure 7**). This study concluded that the implementation of digital technologies has increased the understanding of and provided a solid basis for digital transformation in construction. Also, the digital transformation in construction activity fields is concurrent designing and printing, construction process integration, interfirm relations, automated payment systems, digital construction, and information exchange. Regarding research limitation, the findings were obtained from 36 journal publications. However, it was acknowledged in this article that the subject and the research about it are still emerging. Therefore, this study employed an inductive review approach that isolated conference publications to obtain quality findings. Also, the approach helped in capturing the relevant concepts in the emerging field.

AUTHOR CONTRIBUTIONS

AO carried out the literature review and discussion of findings. MS overviewed the manuscript and organized the contents.

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Construction Industry Training Assessment Framework

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The construction industry suffers from a lack of structured assessment methods to consistently gauge the efficacy of workforce training programs. To address this issue, this study presents a framework for construction industry training assessment that identifies established practices rooted in evaluation science and developed from a review of archival construction industry training literature. Inclusion criteria for the evaluated studies are: archival training studies focused on the construction industry workforce and integration of educational theory in training creation or implementation. Literature meeting these criteria are summarized and a case review is presented detailing assessment practices and results. The assessment practices are then synthesized with the Kirkpatrick Model to analyze how closely industry assessment corresponds with established training evaluation standards. The study culminates in a training assessment framework created by integrating practices described in the identified studies, established survey writing practices, and the Kirkpatrick Model. This study found that two-thirds of reviewed literature used surveys, questionnaires, or interviews to assess training efficacy, two studies that used questionnaires to assess training efficacy provided question text, three studies measured learning by administering tests to training participants, one study measured changed behavior as a result of training, and one study measured organizational impact as a result of training.

Keywords: workforce training, training assessment, Kirkpatrick model, training framework, construction professionals

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INTRODUCTION

Formal learning and training have been shown to increase an employee's critical thinking skills and informal learning potential in any given job function (Choi and Jacobs, 2011). Evaluating training through appropriate assessment is an important aspect of any educational endeavor (Salsali, 2005), especially for assessing training efficacy in real world studies (Salas and Cannon-Bowers, 2001). Examples of training assessment abound in literature across disciplines, for both professionals and non-professionals. For example, bus drivers who attended an eco-driving course achieved a statistically significant 16% improvement in fuel economy (Sullman et al., 2015); recording engineers with technical ear training achieved a statistically significant 10% improvement in technical listening (Sungyoung, 2015); and automatic external defibrillator training of non-medical professionals resulted in a statistically significant reduction in the time to initial defibrillation by 34 s, translating in a 6% increase in survival rate (Mitchell et al., 2008).

Many advancements have been made in construction education assessment at the university level (e.g., Mills et al., 2010; Clevenger and Ozbek, 2013; Ruge and McCormack, 2017). However, within the industry itself, the dearth of workforce training research (Russell et al., 2007; Killingsworth and Grosskopf, 2013) extends to the assessment of construction industry training, particularly assessments of how learning major construction tasks affects project outcomes (Jarkas, 2010). Love et al. (2009) found that poor training and low skill levels are commonly associated with rework, which is a chronic industry problem, representing 52% of construction project cost growth (Love, 2002). Given the potential for loss within the construction industry, in both economic and life safety terms (Zhou and Kou, 2010; Barber and El-Adaway, 2015), it is reasonable to expect that integration of construction industry training assessment practices across the industry would yield improved effectiveness amongst those trained.

To understand and improve current practices for industry training assessment, the following research questions are undertaken:

- What practices have been used to assess construction industry training?
- How closely do construction industry training assessments adhere to established training evaluation standards?
- What survey science practices are typically not integrated in construction industry training?
- What practices (i.e., optimal standards) are appropriate for implementation in construction industry training program assessment?

This paper presents a framework for construction industry training assessment that identifies established practices rooted in evaluation science and developed from a review of archival construction industry training literature. The Kirkpatrick techniques (Kirkpatrick, 1959) for training evaluation serve as the foundation for the framework and relevant survey science best practices are identified and integrated. Assessment methodologies contained within the studies that meet the inclusion criteria are summarized through comprehensive case review and categorized according to the Kirkpatrick Model (Kirkpatrick, 1959) levels. The identified assessment methods are then linked with Kirkpatrick Model guidelines to analyze how closely construction industry training studies have adhered to established training evaluation standards. By analyzing the identified studies and established survey science literature, optimal standards for assessing construction industry training programs are extracted and presented within a construction industry training assessment framework.

The contribution of this research is the creation of a framework with guidelines for assessing industry training that align with the Kirkpatrick Model and have been distilled from published industry training literature and survey science best practices. The case review results and synthesis provide a current snapshot of professional construction industry training assessment criteria, identifying how closely established evaluation standards are met, and more critically, what survey science practices are integrated in assessments. This allows for the integration of established evaluation science into training assessment practices. The intended audience of this paper is construction education and training researchers, professionals, organizations, and groups. The practical implications of this framework are its direct implementation by those conducting training, basis in sound assessment science, and practices extracted from literature.

MATERIALS AND METHODS

Assessment Background

Overview of Evaluation Techniques

The reported efficacy of training has been shown to differ depending on the assessment methodology (Arthur et al., 2003), underlining the importance of the alignment of assessment levels and methods with outcome criteria. Kirkpatrick and Kirkpatrick (2016) define training efficacy as training that leads to improved key organizational results. Studies often use questionnaires after training for assessment; however, participant evaluations and learning metrics evaluate different aspects of success. Questionnaires administered directly following training tend to only measure immediate reaction to the training; therefore, to effectively evaluate training impacts beyond participant satisfaction, an assessment model is recommended. Kirkpatrick (1959) *Techniques for Evaluating Training Programs*, known as the Kirkpatrick Model, is likely the most well-known framework for training and development assessment (Phillips, 1991) and remains widely used today (Reio et al., 2017). It is comprised of four assessment levels: 1) Reaction, 2) Learning, 3) Behavior, and 4) Results.

Kirkpatrick asserts that training be evaluated using the four assessment levels described, and that these are sufficient for holistic training evaluation (Kirkpatrick, 1959). However, since its introduction, several other important evaluation models have been developed, many of which stem from the Kirkpatrick Model. For example, the input-process-output (IPO) model (Bushnell, 1990) begins by identifying pre-training components (e.g., training materials, instructors, facilities) that impact efficacy as the input stage. The process stage focuses on the design and delivery of training programs. Finally, the output stage essentially covers the same scope as the Kirkpatrick Model. Brinkerhoff (1987) six-stage evaluation model goes beyond assessment into training design and implementation. The first stage identifies the goals of training and the second stage assesses the design of a training program before implementation. The remaining four stages fall in line with Kirkpatrick's four levels. Kaufman and Keller (1994) present a five-level evaluation model where Level 1 is expanded to include enabling, or the availability of resources, as well as reaction; Levels 2 through 4 match the corresponding levels in the Kirkpatrick Model; Level 5 goes beyond the organization and presents a method of evaluating the training program on a societal level. Phillips (1998) presents a five-level model that adopts Kirkpatrick's first three levels and expands the fourth level by identifying ways that organizations can assess organizational impact. A fifth level is added that evaluates the true

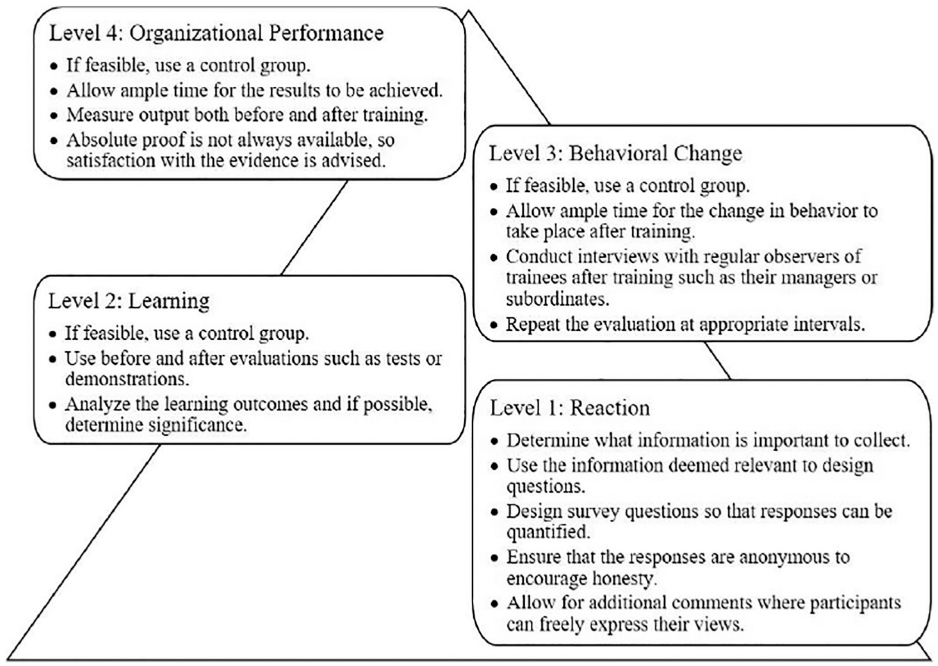

FIGURE 1 | Kirkpatrick model levels and guidelines (Kirkpatrick, 1996).

return on investment (ROI) by comparing the cost of a training program with the financial gain of organizations implementing training.

While developing and designing effective programs are important, these criteria fall outside the scope of this study; which focuses on training assessment implementation and not evaluating the suitability of aspects of the training programs reviewed. Therefore, the Bushnell and Brinkerhoff models have no advantage above the Kirkpatrick Model for this analysis. Similarly, there is not enough information provided in the identified studies regarding social implications as a result of training to warrant use of Kaufman and Keller's or Phillips's five-level models as a basis. From an assessment aspect, the reviewed models essentially stem from and adhere to the four levels found in the Kirkpatrick Model. Because the focus of this research is the assessment of construction industry training programs, and not the design and development of training, the Kirkpatrick Model is well-suited for robust synthesis and extraction of optimal standards for training evaluation methodologies and is therefore used in this study.

The Kirkpatrick Model

Kirkpatrick (1996) asserts that the 1959 model is widely used because of its simplicity. Amongst the population of training professionals, there is little interest in a complex scholarly approach to training assessment. Definitions and simple guidelines are presented in the model to facilitate straightforward implementation (**Figure 1**). The following paragraphs describe each level in more detail.

Level 1: Reaction Within the first level, overall trainee satisfaction with the instruction they have received is measured. While all training programs should be evaluated at least at this level (Kirkpatrick, 1996), learning retention is not measured here. Participant reactions are perceived to be easily measured through trainee feedback or survey question answers (Sapsford, 2006); therefore, surveys are a common means of assessment. From a robust reaction analysis, program designers assess training acceptance and elicit participant suggestions and comments to help shape future training sessions.

Level 2: Learning Within the second level, trainee knowledge gain, improved skills, or attitude adjustments resulting from the training program are measured. Because measuring learning is more difficult than measuring reactions (Level 1), before-and-after evaluations are recommended. These may include written tests or demonstrations measuring skill improvements. Analysis of learning assessment data and use of a control group are recommended to determine the statistical significance of training on learning outcomes, when possible.

Level 3: Behavior Within the third level, the extent to which training participants change their workplace behavior is measured. For behavior to change, trainees must recognize shortcomings and want to improve. Evaluation consists of participant observation at regular intervals following the training, allowing ample time for behavior change to occur. External longitudinal monitoring is more difficult than assessment practices in the previous two levels. A control group is recommended.

Level 4: Results Within the fourth level, the effect that training has on an overall organization or business is measured. Many organizations are most interested (if not only interested) in this level of evaluation (Kirkpatrick, 1996). In fact, "The New World Kirkpatrick Model" (Kirkpatrick and Kirkpatrick, 2016) asserts that training programs should be designed in reverse order from Level 4 to Level 1 to keep the focus on what organizations value most. Common assessment metrics are improved quality, increased production, increased sales, or decreased cost following training. A control group is recommended.

Survey Science Best Practices

Multiple studies have focused on proper formulation of survey questions that can be used across industries. Lietz (2010) summarized the literature regarding questionnaire design, focusing on best practices such as question length, grammar, specificity and simplicity, social desirability, double-barreled questions, negatively worded questions, and adverbs of frequency. With regards to question length, Lietz (2010) recommends short questions to increase respondents' understanding. Complex grammar should be minimized and pronouns should be avoided. Simplicity and specificity should be practiced to decrease respondents' cognitive effort. Complex questions should be avoided and instead separated into multiple questions. Definitions should be provided within the question to give context. For example, a "chronic" health condition means seeing a doctor two or three times for the same condition (Fowler, 2004). The scale used to gauge responses with should also follow the concept of simplicity. Taherdoost (2019) found that while scales of 9 and 10 are thought to increase specificity, reliability, validity, and discriminating power were indicated to be more effective with scales of 7 or less. Social desirability may result in respondents' answering questions based on their perception of a position favored by society. To remedy this bias, Brace (2018) suggests asking questions indirectly, such as "What do you believe other people think?" where respondents may be more likely to admit unpopular views. "Doubled-barreled" questions contain two verbs and should be avoided. Negatively worded questions should similarly be avoided to clarify the meaning. This is particularly the case when the words "no" or "not" are used together with words that have a negative meaning such as "unhelpful." Finally, adverbs such as "usually" or "frequently" should be avoided and replaced with actual time intervals such as "weekly" or "monthly."

Methodology

The methodology consists of three steps:

1. Relevant literature is identified through inclusion criteria; case review is performed to extract and summarize key assessment aspects.
2. Identified construction assessment methodologies are evaluated against the corresponding Kirkpatrick Model level guidelines.
3. An assessment framework is constructed that integrates optimal assessment standards aligned with the Kirkpatrick Model.

Study Selection and Evaluation

A structured literature review is implemented to collect data describing construction industry training assessment for current industry professionals. The objective is to understand how various construction industry training programs that have embedded established educational theory in their design or implementation assess training efficacy. Educational theory-embedded training was selected because it is indicative of a more robust training assessment. Peer reviewed archival literature is searched to determine the state of construction industry training studies that have been documented in scholarly works.

The main search keywords were "construction industry," "education theory," and "training." The main research engines were EBSCOhost library services and Google Scholar; and they were used to identify relevant studies. The following inclusion criteria were established to identify recent, relevant peer-reviewed construction industry training studies published after 2005 for investigation in this study:

1. The training focuses on the current construction industry workforce, including construction workers (W), project managers (M), and designers (D).
2. The training incorporated educational theory in its creation or implementation.

Using the keywords mentioned above, a literature search was conducted resulting in 475 research studies, which increased to 483 through identification of other sources referenced in the initial search results. After removing duplicates and applying the inclusion criteria and additional quality measures, 15 publications were identified for the review, indicating limited research conducted in this area. The selection process is illustrated in the Preferred Items for Systematic Review Recommendations (PRISMA) (Moher et al., 2009) flow chart in **Figure 2**.

The following information was recorded from the relevant publications that met the inclusion criteria: location (i.e., country) where the study took place, educational theory employed, training subject, assessment level corresponding to the Kirkpatrick Model, and assessment methodology. Assessment tools were often referred to as questionnaires, surveys, or interviews. Each of these assessment types was recoded as "questionnaires." A case review summarizes the methods, assessment criteria, and results of the studies identified. The case review is created to provide context of the studies.

Kirkpatrick Model Synthesis

The assessment methodologies within the identified studies were linked to the corresponding guidelines established by the Kirkpatrick Model. The assessment methods within each training program study were evaluated, first to determine the corresponding Kirkpatrick Level, and second to identify adherence to the Kirkpatrick guidelines (Kirkpatrick, 1996) for each level.

Survey Science Synthesis

The identified studies that provided the text of the questionnaires administered to training participants were evaluated against the survey science best practices summarized by Lietz (2010). The

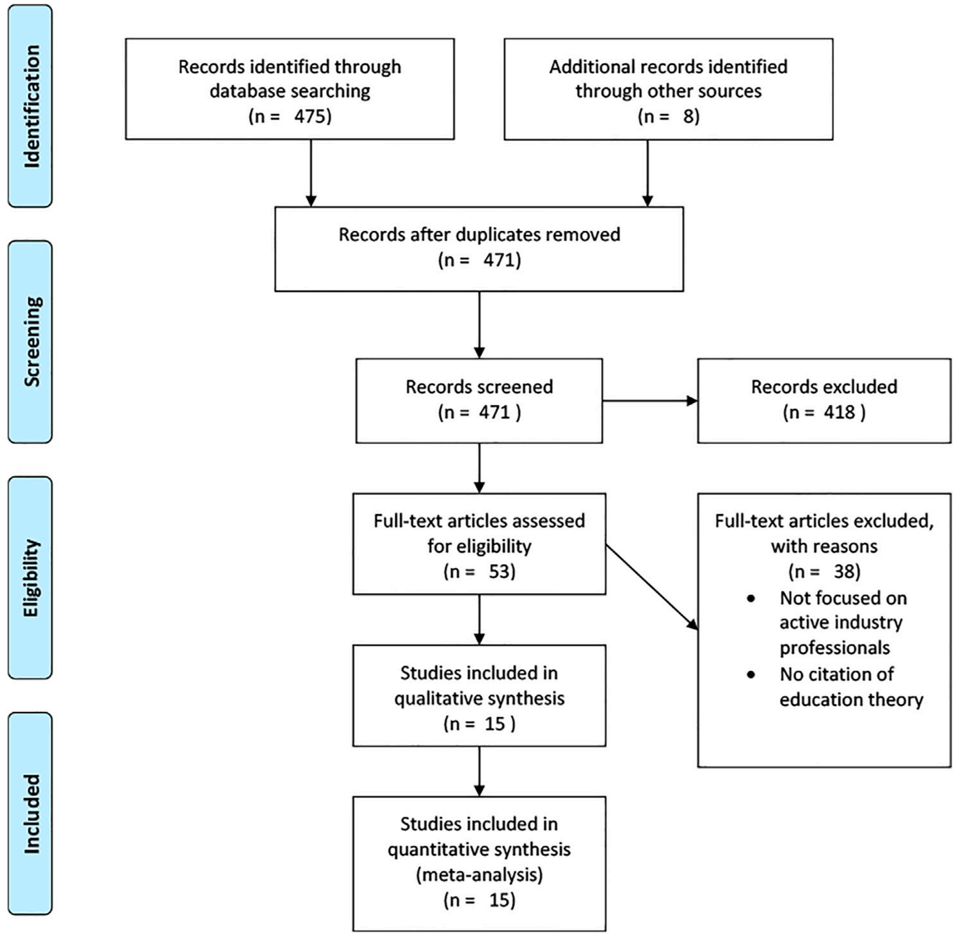

FIGURE 2 | PRISMA flow diagram of literature identification and selection process.

total occurrence of each practice is enumerated so that more common practices are identified.

Construction Industry Training Assessment Framework

The assessment review culminates in the presentation of a framework of optimal practices identified through the synthesis of assessment criteria used in the construction industry training studies and survey science best practices, aligned with the Kirkpatrick Model. The framework includes a summary of Kirkpatrick Model guidelines and practices resulting from the synthesis of identified construction literature and established survey science.

RESULTS, ANALYSIS, AND DISCUSSIONS

Study Selection and Evaluation

Fifteen studies describing education theory-integrated construction industry training met the inclusion criteria selected, listed in alphabetical order in **Table 1**. A short summary of assessment criteria used in each study is provided in the following case review and corresponding ties to the Kirkpatrick Model are established.

Study Number 1

Akanmu et al. (2020) implemented a virtual reality (VR) training focused on reducing construction worker ergonomic risks. The primary assessment method was participant feedback through a questionnaire with both rated questions (1 = strongly disagree, 5 = strongly agree) and open-ended questions, meeting Level 1 standards. Rating questions gauged whether the user interface for the postural training program interfered with the work surface (mean = 2.4), whether the virtual reality display affected performance (mean = 2.7), whether the display was distracting (mean = 1.3), and whether the avatar and color scheme enhanced their understanding of ergonomic safety (mean = 1.2). In open-ended questions, 9 out of 10 participants reported that the VR training helped adjust posture. Two out of ten participants complained that the wearable sensors obstructed movement. The study did not publish the assessment questions directly, and only provided results; therefore, they were not analyzed for survey science best practices outlined by Lietz (2010). It should be noted that mean scores of 1.3 and 1.2 do not appear to be positive as they favor the strongly disagree rating based on the key provided. Additionally, the exact open-ended question text is

TABLE 1 | Construction industry training studies reviewed.

Study number and reference		Country	Educational theory	Subject	Kirkpatrick level	Assessment methodology
1	Akanmu et al. (2020)	United States	Digital game-based learning	Ergonomic safety	1	Questionnaire
2	Begum et al. (2009)	Malaysia	Ajzen's theory	Waste management	1	Questionnaire
3	Bena et al. (2009)	Italy	Andragogy	Safety	4	Injury monitoring
4	Bhandari and Hallowell (2017)	United States	Andragogy	Safety and risk perception	1	Questionnaire
5	Bressiani and Roman (2017)	Brazil	Andragogy	Masonry brick laying	1	Questionnaire
6	Choudhry (2014)	China	Behaviorism	Safety	3	Questionnaire
7	Douglas-Lenders et al. (2017)	Australia	Self-efficacy	Leadership training for project managers	1	Questionnaire
8	Eggerth et al. (2018)	United States	Andragogy	Safety	1	Questionnaire
9	Evia (2011)	United States	The Kirkpatrick model	Safety	1	Questionnaire
10	Forst et al. (2013)	United States	Andragogy	Safety	2	Questionnaire
11	Goulding et al. (2012)	United Kingdom	Digital game-based learning	Offsite production	1	Feedback
12	Mehany et al. (2019)	United States	Long term retention	Confined space training	2	Testing
13	Lin et al. (2018)	United States	Andragogy	Safety	1.2	Questionnaire
14	Lingard et al. (2015)	Australia	Visual pedagogy	Construction health and safety	1	Video-based intervention
15	Wall and Ahmed (2008)	Ireland	Blended learning	Project management	1	Computer simulation implementation

TABLE 2 | Connections to the Kirkpatrick guideline from 15 construction industry training studies.

Kirkpatrick level	Attributes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
1: Reaction[a]	Design survey questions so that responses can be quantified	x	x	—	x	x	—	x	x	x	—	—	—	x	—	—	8
	Ensure that the responses are anonymous to encourage honesty	x	x	—	x	x	—	x	x	x	—	—	—	x	—	—	8
	Allow for additional comments where participants can freely express their views	x	—	—	—	—	—	—	—	—	—	—	—	—	x	—	2
2: Learning	If feasible, use a control group	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0
	Use before and after evaluations such as tests or demonstrations	—	—	—	—	—	—	—	—	—	x	—	x	x	—	—	3
	Analyze the learning outcomes and if possible, determine significance	—	—	—	—	—	—	—	—	—	x	—	x	x	—	—	3
3: Behavioral Change	If feasible, use a control group	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0
	Allow ample time for the change in behavior to take place after training	—	—	—	—	—	x	—	—	—	—	—	—	—	—	—	1
	Conduct interviews with regular observers of trainees after training such as their managers or subordinates	—	—	—	—	—	x	—	—	—	—	—	—	—	—	—	1
	Repeat the evaluation at appropriate intervals	—	—	—	—	—	x	—	—	—	—	—	—	—	—	—	1
4: Organizational Performance	If feasible, use a control group	—	—	x	—	—	—	—	—	—	—	—	—	—	—	—	1
	Allow ample time for the results to be achieved	—	—	x	—	—	—	—	—	—	—	—	—	—	—	—	1
	Measure output both before and after training	—	—	x	—	—	—	—	—	—	—	—	—	—	—	—	1
	Absolute proof is not always available, so satisfaction with the evidence is advised	—	—	x	—	—	—	—	—	—	—	—	—	—	—	—	1

[a]*Note: The first two guidelines associated with Level 1 are not listed as they were not contained in the studies.*

not provided, and the article states that they are asked to encourage improvement of training in the future. This does not follow established survey guidelines, as this question will not yield quantifiable results.

Study Number 2

Begum et al. (2009) administered a survey to local contractors in Malaysia to measure the attitudes and behaviors of contractors toward waste management, categorizing this assessment as Level 1. The results found a positive regression coefficient ($\beta = 2.006$; $p = 0.002$) correlating education to contractor waste management attitude; making education one the most significant factors found in the study. The study did not provide the actual questions asked on the questionnaire, but instead stated that the following "attitudes" were assessed: general characteristics, such as contractor type and size; waste collection and disposal systems;

TABLE 3 | Survey science best practices connection to construction industry training studies.

Survey question best practices	1	2	4	5	7	8	9	11	13	14	15	Total (%)
Survey questions provided	x	x	x	✓	x	✓	x	x	x	x	x	18
Question length	-	-	-	✓	-	✓	-	-	-	-	-	100
Grammar	-	-	-	✓	-	✓	-	-	-	-	-	100
Specificity and simplicity	-	-	-	✓	-	✓	-	-	-	-	-	100
Social desirability	-	-	-	x	-	✓	-	-	-	-	-	50
Double-barreled questions	-	-	-	✓	-	✓	-	-	-	-	-	100
Negatively worded questions	-	-	-	✓	-	✓	-	-	-	-	-	100
Adverbs of frequency	-	-	-	✓	-	✓	-	-	-	-	-	100
Response scale is reasonable	✓	-	x	x	✓	-	x	-	-	-	-	40
Quantifiable results[a]	✓	✓	✓	✓	✓	✓	x	x	✓	x	x	64
Allowing for additional comments[a]	✓	-	-	x	x	-	x	-	-	-	-	25

[a]*Note: ✓ indicates the best practice was met; 'x' indicates the best practice was not met; '-' indicates adherence to the best practice could not be assessed.*

waste sorting, reduction, reuse and recycling practices; employee awareness; education and training programs; attitudes and perceptions toward construction waste management and disposal; behaviors with regard to source reduction and the reuse and recycling of construction waste. With this information, it is difficult to determine how closely questionnaire guidelines were followed.

Study Number 3

Bena et al. (2009) assessed the training program delivered to construction workers working on a high-speed railway line in Italy. The assessment analyzed injury rates for workers before and after training and found that the incidence of occupational injuries fell by 16% for the basic training module, and by 25% after workers attended more specific modules. This is a Level 4 evaluation because the overall organizational outcomes were assessed.

Study Number 4

Bhandari and Hallowell (2017) proposed a multimedia training that integrated andragogy (i.e., adult learning) principles to demonstrate the cause and effect of hand injuries during construction situations, focusing on injuries caused by falling objects and pinch-points. A questionnaire asked participants to rate the intensity of different emotions using a 9-point Likert scale both before and after the training simulation was distributed. Overall, workers reported a statistically significant increase in negative emotions such as confusion (p = 0.01), fear (p = 0.01), and sadness (p = 0.01) after they had been trained. Statistically significant decreases in positive emotions such as happiness (p = 0.01), joy (p = 0.01), love (p = 0.01), and pride (p = 0.01) were also reported by trainees. Because gauging trainee response are the main assessment tool, this is classified as a Level 1 evaluation. In total, eighteen emotions were assessed, making the survey rather lengthy and possibly inducing cognitive fatigue or confusion. Additionally, a 9-point Likert scale adds a wide range of possible options to choose from, which is higher than the recommendation by Taherdoost (2019) of a 7-point scale. A shorter survey with fewer options might improve the results generated by this study.

Study Number 5

Bressiani and Roman (2017) used andragogy to develop a training program for masonry bricklayers. Questionnaires used to assess the participant feedback found that andrological principles were met in more than 92% of responses. Because guaging trainee response are the main assessment tool, this is classified as a Level 1 evaluation. The study presented training participants with a 24-question survey found in the appendix of their study. The questions themselves are short, simple, and pertain to a singular topic, complying with survey best practices. However, the response options are given on a 0–10 scale. Similar to Bhandari and Hallowell's 9-point scale, this number of response choices can add confusion and complexity when respondents answer the questions.

Study Number 6

Choudhry (2014) implemented a safety training program based on behaviorism. Safety observers monitored the use of personal protective equipment (PPE) such as safety helmets, protective footwear, gloves, ear defenders, goggles or eye protection, and face masks over a 6-week period. Safety performance in the form of utilization of PPE increased from 86%, measured 3 weeks after training, to 92.9%, measured 9 weeks after training. This is classified as a Level 3 evaluation because behavior changes were observed and noted. Further, external observers were used and data were collected over time, adhering to Kirkpatrick Level 3 guidelines.

Study Number 7

Douglas-Lenders et al. (2017) found an increase in self-efficacy of construction project managers after a leadership training program was administered. This assessment was conducted through a questionnaire that presented questions on a 5-point Likert scale; which was used to gauge trainee self-perception as a result of training. Learning confidence, learning motivation, and supervisor support received average scores of 4.23, 3.86, and 3.84 respectively from training participants. Because surveys are the main assessment criteria this is classified as a Level 1 evaluation. The study did not publish the assessment questions directly, and only provided results; therefore, they were not analyzed for survey science best practices.

Study Number 8

Eggerth et al. (2018) evaluated safety training "toolbox talks," which are brief instructional sessions on a jobsite or in a contractor's office. The study involves a treatment group that experienced training, as well as a control group answered a questionnaire. The trained group rated the importance of safety climate statistically significantly higher than the control group ($p = 0.026$). Because guaging trainee response are the main assessment tool, this is classified as a Level 1 evaluation. Sample questions are recorded in the study, however, the questionnaire in its entirety is not presented. However, based on the sample questions, it is likely that the questionnaire generally falls in line with survey standards.

Study Number 9

Evia (2011) evaluated computer-based safety training targeted toward Hispanic construction workers. Based on interviews with the participants, a positive reaction to the training with significant knowledge retention was achieved. This study also did not present the questionnaire in its entirety; however, it is mentioned that the evaluation measured reaction. Workers were able to give ratings such as "very interesting," and "easy" with regards to a video watched during the training; however no numerical assessment was given. Because guaging trainee response are the main assessment tool, this is classified as a Level 1 evaluation. The study did not publish the assessment questions directly; therefore, they were not analyzed for survey science best practices.

Study Number 10

Forst et al. (2013) evaluated a safety training targeted toward Hispanic construction workers in seven cities across the United States. Questionnaires that were administered to the training participants indicate demonstrated improvements in safety knowledge. The results found a statistically significant knowledge gain for the questions regarding fall prevention and grounding from the pre-training and post-training questionnaires ($p = 0.0003$). This type of evaluation is classified as Level 2 because the learning outcomes of training were measured. The pre-training and post-training testing guidelines appear to have been met throughout this study.

Study Number 11

Goulding et al. (2012) present the findings of an offsite production virtual reality training prototype. Feedback of training was requested, and the feedback was summarized as being positive. Because guaging trainee response are the main assessment tool, this is classified as a Level 1 evaluation. No numerical assessment was provided and the study did not publish the assessment questions directly; therefore, they were not analyzed for survey science best practices.

Study Number 12

Mehany et al. (2019) evaluated a confined space training program administered to construction workers. A test was administered to the training participants and the results found that the participants scored below average, even after attending the training on the subject. A score of 11/15 is taken to be the United States national average. The participants scored an average of 9.3/15. This average was further broken into a non-student sample (industry professionals) that scored an average mean of 8.3 and a student sample that scored 9.5. This is classified as a Level 2 evaluation because the learning outcomes of training were measured. Diversity in the population of examinees provided the authors with interesting analysis opportunities and the ability to speculate on the difference in scores between the two groups, which is desirable in learning evaluations.

Study Number 13

Lin et al. (2018) used a computer-based three-dimensional visualization technique, designed by adult education subject matter experts, to train Spanish-speaking construction workers on safety and fall fatality. Interviews were conducted to evaluate the training program. 64–90% of English-speaking workers achieved the intend results, 73–83% of Spanish-speaking workers achieved the intended results. 100% of Spanish-speaking workers reported that they would recommend the training materials to others while only 46% of English-speaking workers reported that they would recommend the training materials to others. Because both interviews and tests were conducted this is classified as a Level 1 and Level 2 evaluation. From a Level 1 perspective the study presents the results in an "evaluation of validation" format without referencing the exact questions asked. This makes it difficult to assess how closely question format guidelines were followed. From a Level 2 perspective a set of questions to assess knowledge gain is presented. Both English and Spanish speaking participants were tested. Six questions were included on the test to assess participant knowledge gain after the training. Similar to the previous study, the diversity in the populations provides analysis opportunities to assess learning outcomes as a result of training.

Study Number 14

Lingard et al. (2015) evaluated the use of participatory video-based training to identify safety concerns on a construction jobsite. As a result of this training, new health and safety rules were generated by participants. The training was based on viewing the recordings and success was measured by workers' ability to establish new safety guidelines to enable compliance. Because feedback was taken into consideration this is classified as a Level 1 evaluation. This study culminated in the participants sharing their reactions to the training in a group setting. While the reactions were captured, the study did not publish the assessment questions directly; therefore, they were not analyzed for survey science best practices.

Study Number 15

Wall and Ahmed (2008) explore a training delivered to Irish construction project managers on construction management computerized tools. Participants reported the program increased their understanding of construction problems and decisions. Because participant feedback was gathered this is classified as a Level 1 evaluation. However, the study did not capture participant responses in an explicit way, but rather it was presented that feedback was favorable and no numerical assessments were presented.

Case Review Summary

This case review found that ten studies (67%) used surveys, questionnaires, or interviews to assess the training programs, three studies (20%) measured learning by administering tests to training participants, one study measured changes in behavior resulting from training, and one study measured organizational impact a result of training. Attributes of the assessment methodologies that complied with Kirkpatrick standards or established survey science best practices were noted as positively complying with Level 1 assessment standards, which are summarized in the survey science synthesis. Studies that complied with Level 2–4 standards typically complied with the guidelines set forth by Kirkpatrick, however it is surprising that so few studies utilized these methodologies. This is especially the case with Level 4 evaluation standards. Organizations ultimately seek to understand how training might impact performance on an organizational level; yet of the 15 studies analyzed, one complied with this standard of evaluation. Gaps identified in the review of the studies inspired the guidelines outlined in the Construction Industry Assessment Framework presented in this paper.

Kirkpatrick Model Synthesis

Although the first two Level 1 guidelines were excluded from the analysis, amongst the remaining three Level 1 guidelines, one study (Akanmu et al., 2020) included all three assessment guidelines, while seven studies met two Level 1 guidelines, and one study met one Level 1 guideline. The three studies that met Level 2 guidelines were identical in that they excluded the use of a control group and adhered to all other guidelines. Similarly, the only study (Choudhry, 2014) that met Level 3 guidelines excluded the use of a control group and adhered to all other guidelines. One study (Bena et al., 2009) provided a Level 4 evaluation that met all associated guidelines. This information is shown in **Table 2**.

Survey Science Synthesis

Of the studies that used Level 1 criteria for their assessment methodology, two (18%) provided the text of the survey questions presented to training participants. The remaining studies did not publish the assessment questions directly. Bressiani and Roman (2017) presented the questionnaire in its entirety. All survey science recommendations summarized by Lietz (2010) were met except for guarding against social desirability, implementing a reasonable response scale, and allowing for additional comments. Eggerth et al. (2018) only presented sample questions from the questionnaire distributed to participants, however, all survey recommendations that could be analyzed were met. Analysis of the response scale reveals that of the five studies that provided their scales, two (40%) adhered to optimal scale standards of seven or less. 64% of studies provided results that could be quantified. 25% of studies that were analyzed for allowing additional comments were found to have done so. The percentage was derived by dividing the number of times a practice was met by the number of times a practice was not met. When a practice could not be assessed for a study, this field was excluded from the calculation. This information is shown in **Table 3**.

Construction Industry Training Assessment Framework

Survey results may be skewed by the questions asked (Dolnicar, 2013), and poorly written questions often result in flawed data (Artino, 2017). When one considers that most construction industry training studies evaluate efficacy by attempting to collect the reaction of participants, it is important that the questions asked be made available for future study and analysis. For this reason, the framework provides extensive recommendations to improve Level 1 analyses. Additionally, because only 20% of studies that used questionnaires as their means of assessment provided the questionnaire text, the current adherence of Level 1 construction industry training assessment best practices remains widely unknown. Moving forward, it is of the utmost importance that this information be provided to support robust Level 1 assessment. Additionally, Taherdoost (2019) recommends a 7-point Likert type scale as to not overwhelm participants with a high number of response options. When composing open-ended questions, efforts should be made to frame the questions in a way that will yield results that are quantifiable. While analysis of open-ended questions is rare, the results can be very valuable (Roberts et al., 2014). Due to the lack of complete survey question text included in most studies, it is recommended that survey questions be contained within training studies so that the results can be fully analyzed.

The simplest method for analyzing learning development as a result of a training program is an evaluation to be administered before and after a training program (Kirkpatrick, 1996). Kirkpatrick recommends the use of a control group. However, in literature it was observed that a control group was rare. Cost, resources, and time could be contributing factors, however, for the sake of analysis these circumstances should be made clear. The study presented by Mehany et al. (2019) measured learning outcomes against an industry wide average, which provides a benchmark for the results of a given training program. If possible, this should be the norm, as it gives a standard by which a given training program is analyzed. Several studies analyzed the evaluation results for statistical significance. This should be done when possible to lend more credibility to the results.

To measure the extent to which training participants change their workplace behavior, observations are collected over time. Similar to the learning level, a rationale should be provided when a control group is not used. The study presented by Choudhry (2014) details the intervals at which observations are made. This should be standard practice and measurements at these intervals should be reports so that a progression can be seen. Additionally, is it known that people may change their behavior unexpectedly if they know that they are being observed (Harvey et al., 2009), and for this reason, observations should be made as inconspicuously as possible.

TABLE 4 | Framework for construction industry training assessment

Level 1: Reaction

Design survey questions that will ensure the collection of relevant data from participants in a manner that can be quantified, allowing for anonymity and additional participant feedback

- To provide justification for survey results, present the process of identifying relevant information to be gathered by the surveys
- Generate questions that will encourage training participants to provide information that is relevant to the training designers
- Adhere to survey science best practices outlined in this paper
- Develop questions so that results may be quantified. Likert type scales should be no more than seven points to avoid confusion of participants
- While open-ended questions are encouraged, they should be framed in a way so that the responses are quantifiable
- Include survey question text in descriptions of the training (e.g., journal publications) to add to the body of knowledge

Level 2: Learning

Create evaluations for training participants that can be completed before and after a given training to measure learning progress. Analyze the results and determine the statistical significance of changes in knowledge

- Rationalize the lack of a control group if one is not utilized
- If possible, determine an industry average of test results to compare the results of trainees to the average of the overall industry
- Analyze the learning outcomes for statistical significance for each individual question so that specific learning outcomes can be identified, and improvement can be made where no significance is found

Level 3: Behavioral Change

After the allotment of ample time for participants to change their behavior following training, conduct observations and interviews with regular observers to quantify the change in behavior, repeating the evaluation at appropriate intervals

- Rationalize the lack of a control group if one is not utilized
- Provide time intervals of when behavioral observances occur so change in behavior can be monitored over time
- If possible, monitor behavioral changes discretely so that participants are not only changing their behavior when they are being observed

Level 4: Organizational Performance

After allowing ample time for results to be achieved, measure the output before and after training

- Rationalize the lack of a control group if one is not utilized
- Generate a metric for organizational performance prior to training implementation so data can be more easily collected
- Be sure to note pre-training performance levels so changes in performance can be measured
- Identify other factors that may contribute to changes in performance to isolate the effect of training as a factor

When measuring organizational performance, the same care to rationalize the lack of a control group should be included in a training study; as is the recommendation for the Learning and Behavioral Change levels. While Kirkpatrick includes common metrics for measuring training effectiveness at this level such as decreased cost or increased revenue, these metrics are not always clearly defined. The metric by which an organization would like to measure effectiveness should be clearly identified in a training study. To accurately organizational change, pre-training levels must be noted. Kirkpatrick (1996) notes that factors other than training may also affect overall organizational performance. These factors should be identified and noted in a training study.

With this information in mind, the construction industry training framework (**Table 4**) is aligned using Kirkpatrick Model guidelines with the additional knowledge acquired by the synthesis of the identified studies and survey science best practices. Gaps found in the studies, such as the lack of information surrounding how survey questions were chosen, contribute to the framework by emphasizing this type of information that was notably missing across all studies analyzed.

CONCLUSION

This study provides a comprehensive literature review of educational theory-integrated construction industry training focusing on assessment methodologies used in construction industry training literature. Assessment practices identified through case review were compared against the Kirkpatrick Model, a well-known and widely used assessment model. Assessment methodologies in the literature were synthesized with corresponding levels found in the Kirkpatrick Model to analyze how closely the industry adheres to established training evaluation standards. The studies that utilized questionnaires as their means of assessment and provided the text of the questions asked were evaluated against survey science best practices. This study culminates in the creation of a training assessment framework by extracting the practices used in the identified studies so that future assessment methodologies can be implemented, tested, and presented effectively, thus advancing construction industry training. The specific findings of this study are that two-thirds (67%) of identified studies used surveys, questionnaires, or interviews to assess training efficacy. Of the studies that met the inclusion criteria, 73% (11/15) were designed to assess reaction, 20% (3/15) assessed learning, and 7% (1/15) assessed each behavior and organizational impact. Kirkpatrick Levels 2 to 4 assessments implemented in construction literature typically met the Kirkpatrick guidelines; however, Level 1 guidelines were met by 18% (2/11) of the studies. Two of the ten studies (20%) that used questionnaires to assess training efficacy provided question text, and of these, one study followed survey science best practices completely. The following survey science best practices are typically not integrated: accounting for social desirability, implementing a reasonable response scale, and allowing for additional comments. Finally, archival construction industry training literature and survey science best practices were synthesized and aligned with Kirkpatrick (1959) *Techniques for Evaluating Training Programs* to create a framework for construction industry training assessment.

The issue of assessment methodologies is found within archival published literature and appears to be an industry-wide issue. Opportunity exists to implement training programs coupled with optimal assessment methodologies grounded in established educational assessment research. Further opportunities exist to present techniques for measuring organizational outcomes (Level 4), as only one of fifteen studies reviewed used this criterion to assess training. The findings of this research indicate that there is an opportunity to introduce more robust metrics prior to training implementation to assess training at the organizational level, rather than relying on Level 1 through 3 assessment results.

This paper is relevant to the current state of construction industry assessment by presenting a proposed construction industry assessment framework modified from the original Kirkpatrick Model to address gaps found in the model, identified best practices, and relevant practices found in the studies analyzed throughout this paper. While the assessment strategy proposed in this paper is based on best practices, such as survey science best practices to measure reaction, as well as identified practices that measure learning, behavior, and organizational performance, future research is needed to apply the proposed framework to training programs so that its efficacy may be demonstrated.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

HJ provided the conceptual design of this research, conducted the literature review, collected data, developed the initial text, and revised the text through input of the co-authors. CF provided conceptualized the overall project methodology and presentation of results and contributed significantly to draft revisions. IN, CP, CB, and YZ revised early and late versions of the text and provided regular feedback and guidance.

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Using Real-Time Tracking of Materials and Labor for Kit-Based Logistics Management in Construction

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Improved productivity and the elimination of waste are key goals for lean methods in construction production control. One such lean method is a kit-based logistics management in which task-based materials are delivered just-in-time and aligned with assembly operations on-site. Digital platforms could enable a situational awareness of work and material flows, potentially increasing the benefit and applicability of kitting. The aim of the current research is to utilize a real-time indoor tracking of material and labor flows to evaluate an assembly kit–based management of construction projects. We propose a linked data framework to connect labor, material, and scheduling information to integrate heterogenous data. The contribution of the study is threefold: first, a feasible method is developed to enable real-time detection of work and material flows inside the building for logistics management purposes. Second, several key performance indicators for effective evaluation of kit-based production flow in construction are provided, which allows management to tackle root causes of problems and to enhance timely and productive logistic solutions. Thirdly, by applying the linked data method, the study introduces a novel approach to integrate heterogenous data from both indoor tracking and schedules.

Keywords: real-time tracking, construction management, linked data framework, material and labor tracking, data integration, kitting logistics solutions

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INTRODUCTION

Construction sites are frequently thought of as chaotic environments in which waste occurs as a consequence of complex on-site management. As a result, sites suffer from productivity loss and waste related to crews' waiting times, rework, unnecessary movement, material handling, and unused inventories in workspaces and of materials (Sacks et al., 2010). This complexity has motivated the development of several production control approaches in construction (Zhao et al., 2019). Lean construction principles are often applied to enhance workflows and eliminate waste by focusing on workflow variability to improve overall project performance (Thomas et al., 2002). The variability of flow is a key root cause of waste (Seppänen et al., 2010), and therefore measuring and addressing variability is important to eliminate waste and enhance productivity. In this regard, field material management has become a crucial management process (Grau et al., 2009) to address the variability of material flows, to minimize waste, and to ultimately improve project performance.

In the context of material flows, the construction process includes numerous wasteful activities that result from material mishandling on-site. For example, Teizer et al. (2020) monitored shell and interior construction and indicated the notable wasteful activities, including 1) unnecessary handling of material (10%), 2) searching for the right resources (6%), and 3) waiting to use the resource (3%), all of which caused wasted effort related to material mishandling. Misplaced materials cause waste such as rework and delays in tasks (Ju et al., 2012), both of which hinder labor performance. The spaces used to store materials can also potentially block workflows (Arbulu and Ballard, 2004) and affect production progress. Site managers and engineers thus must improve material handling and production flows by utilizing materials at the right time and in the right location.

A kitting logistics solution synchronizes material deliveries with workers' daily tasks into work location levels (Tetik et al., 2020) and could play a key part in stabilizing production flows. Assembly kits, which are carriers that contain material parts for different tasks (Hanson and Medbo, 2012), are transported directly to work locations so the materials can be quickly utilized or installed by workers in the right places without being stored on-site (Tommelein and Li, 1999). Still, kitting practices face the challenges of monitoring in time and efficiently for the direct involvement of workers who use the material batches in work locations. For example, previous methods for evaluating the impacts of kitting practices were based on manual observations and videos (Tetik et al., 2020), which makes evaluating the solution both labor intensive and time consuming. Kitting logistics practice requires smooth information flows among different operations: a situation that also leads to the potential for automation (Zheng et al., 2020).

The use of automated tracking solutions for material management could address these challenges and enhance construction productivity and workflow by providing site managers with easy-to-use metrics to evaluate the process of flows. In building projects, automated material monitoring could help workers know the locations of materials. In this way, searching times for materials are eliminated, productivity is improved, and material handling efficiency is enhanced (Gurmu, 2019).

Despite the expected benefits for site management from localization technologies (Grau et al., 2009), little research has been conducted on tracking systems that cover both materials and workers to support lean principles for enhancing material management and related workflows. Although the collection of tracking data based on labor and material could improve construction material and workflow management, such data is still isolated from the scheduling information of planned on-site operations. Such fragmentation leads to difficulties for various stakeholders when evaluating and comparing the actual labor and material flow situation with the planned conditions based on an integrated database. The worker and material positioning data thus should be combined with the scheduling information in order to investigate the schedule compliance of labor and material interactions.

The linked data approach is a set of design principles within Semantic Web technologies for publishing data in a structured format (Bizer and Schultz, 2009). Such an approach can structure heterogenous data with interlinks to provide formalized and structured data integration. The linked data approach also provides a machine-readable format for computers to understand the meaning of the data so they can produce meaningful query results. While construction industry researchers have investigated these capabilities of the linked data approach (Pauwels et al., 2015), they have yet to use the linked data approach to integrate the positional data of workers and materials with scheduling data.

Based on the above background, our aim is to improve the management of kit-based practice by implementing a passive indoor tracking solution to automatically detect the presence of multiple workers as well as material kits delivered directly to various work locations. We then evaluate the interactions of the material kit and labor flows. Previous research has indicated substantial periods of time when workers are absent from work locations (Zhao et al., 2019), so we consider an investigation of how the kitting solution influences the presence of workers to be an interesting line of research. New insights could also be gained relevant to the evaluation of material management practice (e.g., the kitting solution) and enhancement potentials by tracking both labor and material kits at the same time. Finally, a linked data framework is proposed to unite external data streams (e.g., scheduling information) to ensure data model interoperability and to evaluate the compliance of workers with material kits against the schedule. A broader image of construction resource interrelations thus can be established for future application development.

TECHNICAL BACKGROUND

In this section, the technical background is reviewed from previous studies related to tracking technologies that have been applied in construction for labor and material monitoring, linked data, and Semantic Web technologies. Tracking technologies can be divided into vision- and radio-based tracking methods. **Table 1** summarizes the previous tracking applications used in the construction industry and presents conclusions from research related to our empirical study on tracking solutions for material and labor flows in construction.

Vision-Based Tracking in Construction

Several vision-based methods have been proposed and implemented for monitoring site occurrences involving labor, material, and equipment. The methods are generally easy to deploy and are non-intrusive (Cai and Cai, 2020), although achieving smooth and continuous tracking that is satisfactory for labor and material flows could be a complex undertaking. For instance, recent research (Asadi et al., 2019) examined the possibility of using Building Information Modeling (BIM) coordinate system from camera poses of image frames, which enabled localization and mapping items between image frames and BIM views. The research demonstrated the effectiveness of real-time registration of images with BIMs, which could potentially enhance visibility of tracking process for resources such as labor or materials in the BIM platform. However, the method heavily depends on camera pose estimation and the interior structure of the buildings such as curved walls or arches may be prone to higher error of analysis. Those limitations may complicate the generalizability of applying this method as the use of a secondary positional sensor such as inertial

TABLE 1 | Previous research and conclusions related to our study.

Research	Tracking solution	Main results	Conclusions directing our study
Angah and Chen (2020): Tracking multiple construction workers through deep learning and the gradient based method with re-matching based on multi-object tracking accuracy	Vision-based technology: video cameras	The authors tested and illustrated a multiple human tracking framework which enables automatic detection, matching and re-matchig	The tracking solution enables multiple human monitoring but can encounter heavy interference for issues such as scale variations, appearance similarity, occlusions, posture variations, abrupt movement etc., thus hindering the tracking and detecting of labor and material flows indoors
Cai et al. (2019): Two-step long short-term memory method for identifying construction activities through positional and attentional cues	Vision-based technology: construction video cameras	The authors presented a working group identification method followed by activity recognition based on both positional and attentional cues, to recognize complex interactions from videos	The method allows for identifying construction activities through positional and attentional cues so that the interaction details of multiple entities captured by videos could be recognized, but the framework relies on positional and attentional cues computed based on manually annotated states of individual entities. Furthermore, the method was only tested outdoor construction projects, so the indoor environment is yet to be experimented
Kim et al. (2019): Remote proximity monitoring between mobile construction resources using camera-mounted UAVs	Vision-based technology: unmanned aerial vehicle (UAV)-assisted visual monitoring method	The authors proposed a UAV visual monitoring solution that automatically measures proximities (actual distance from 2D images captured from a UAV)	The method is useful for enabling automatic measurement of actual distances among construction entities which makes it possible for improving accuracy of interpreting the actual interactive activities of labor and materials in our case. However, the framework underwent difficulties to obtain clear state of an object due to obstruction of noises such as sands which may cause false-positive results. Furthermore, the feasibility of implementation UAV into indoor environment can be also challenging
Guven and Ergen (2021): Tracking major resources for automated progress monitoring of construction activities: masonry work case	Radio-based technology: RFID	The authors presented an automated progress monitoring system that utilized RFID technology to track a masonry task activity for multiple resources in construction	The tracking method can determine construction progress by fusing sensor data collected from multiple resources. The overall progress reached 95% accuracy which potentially contributed to estimating labor and material interactions onsite. However, the method was only applied on masonry task, so the accuracy of other tasks is yet to be tested. Furthermore, The RFID sensors were installed in tower crane to enable floor-level tracking detail, but at this stage the floor information of where the masonry materials were delivery was entered manually which would impact the whole automated progress monitoring
Ryu et al. (2019): Automated action recognition using an accelerometer-embedded wristband-type activity tracker	Radio-based technology: accelerometer-embedded wristband-type activity tracker	The study allows for automatic construction action recognition using a single wrist-worn sensor so that the characteristics of workers' actions can be suggested	The tracking approach is good for capturing workers' action in construction sites, which has potential for detecting ongoing activities, but the method relies on predetermined and labeled action classification so the method may work well on standardized and repeated actions but not the non-repetitive ones. Furthermore, the study did not consider material movement but only focused on workers, so the interaction of labor and materials' movements were not possible to detect

(Continued on following page)

TABLE 1 | (*Continued*) Previous research and conclusions related to our study.

Research	Tracking solution	Main results	Conclusions directing our study
Zhao et al. (2019): Real-time resource tracking for analyzing value-adding time in construction	Radio-based technology: BLE	The authors implemented a BLE tracking system to detect and evaluate workers' uninterrupted presence on-site at the project level	The tracking method allows for passive and automated monitoring of workers' presence on-site, which enables the possibility of continuous tracking of labor flows; the research did not consider material tracking, however, so the interaction of workers and materials in work locations was unknown
Zhang et al. (2021). Wireless Monitoring–Based Real-Time Analysis and Early-Warning Safety System for Deep and Large Underground Caverns	Radio-based technology: ZigBee and general packet radio service (GPRS)	The study demonstrates a proposed integration technology of real-time analysis and safety early warning can timely detect abnormalities from monitoring process and stepwise evaluation results	The combined networks of using both ZigBee and GPRS provided timely and reliable data support of detecting abnormalities of workers' tracking records. The method could be useful in our case by adding early-alert mechanism to enable automatic operation intervention possibilities from site managers when the abnormalities of labor and material movement show notable. However, the method was only applied in underground environment and the scope of the study was focused on construction safety therefore whether the method could also enhance onsite operation and productivity remains unknown
Yang et al. (2020). Automated PPE-Tool pair check system for construction safety using smart IoT	Radio-based technology: Wireless Wi-Fi module	The study developed an automated personal protective equipment (PPE) based tool for pair checking of workers and their equipment using the internet of things (IoT) with Wi-Fi modules tagged on the PPE.	The method works efficiently checking paired workers and their tools and materials onsite, which has good potentials to be expanded for checking effectiveness of workers using the tool or materials. However, the method was only tested in a lab experiment, so the challenges revealed in the lab test (such as heavy consumption of battery using Wi-Fi module and obstruction of low illumination) should also be assessed in real construction projects for evaluation.

measuring unit (IMU) and ultrawide band (UWB) may often be needed to address these issues (Asadi et al., 2019).

Despite the possibility of identifying site activities and detecting task status from workers (Luo et al., 2018), the current state-of-the-art vision-based methods may not achieve our aim of tracking both material and labor due to challenges in long-term and robust monitoring of multiple objectives (Cai and Cai, 2020). For our use case, each work location would have to have a camera to ensure the visibility of resources on-site for the entire tracking period; in addition, multiple tracked resources (e.g., workers and materials) might interfere in the view and occlude each other within confined work locations such as apartments. Given the requirement for extensive data sets while training the system (e.g., Luo et al., 2018) and the demands for proper shooting angles from cameras (Zhang et al., 2018), these complexities mean that vision-based tracking solutions may not be practical for analyzing the interactive movement of labor and materials.

Radio-Based Tracking in Construction

Another category of sensor-based monitoring consists of radio-based tracking technologies, which are already being applied in many construction projects. Such technologies are typically based on radio signals that are sent and received among tags (such as beacons) and gateways (Cai and Cai, 2020; Dror et al., 2019). Radio-based tracking technologies are less accurate compared with vision-based tracking technologies (over 1 m for radio-frequency identification [RFID] and Bluetooth Low Energy [BLE] technology), but they are reliable in tracked object detection and identification during the tracking period (Cai and Cai, 2020). Because of the capability of providing reliable information to exclude false detection (Cai and Cai, 2020), radio-based tracking technologies may be more suitable for analyzing the interactions of multi-resource movements when the constant accuracy of resource identity is required during the entire monitoring period.

Some common tracking methods include Zigbee (Zhang et al., 2021), accelerometer wristband (Ryu et al., 2019), Wi-Fi module (Yang et al., 2020), the aforementioned RFID (Guven and Ergen

2021) and BLE (Olivieri et al., 2017; Park et al., 2017; Zhao et al., 2017). These methods all appear to eliminate the effort involved in manual data collection in construction while being accurate and providing in-time data feedback through an automated process. For instance, the RFID solution enables tracking by attaching tags that are active, semi-active, or passive and having scanners or antennas read the tags (Ergen et al., 2007; Li et al., 2020).

The advantage of passive RFID technology is that those tags do not need a separate power supply and are small, inexpensive, and suitable for nearly all kinds of materials (Teizer et al., 2020). This solution would be helpful for detecting material flows in different work locations in parallel with workers' movements. Passive RFID tags cannot be used in large-scale environments, however (Wu et al., 2019), and potential signal blocking under chaotic and dynamic indoor construction conditions still causes challenges in the signal quality of this tracking method (Teizer et al., 2020; Costin et al., 2012). In recent study, RFID tracking methods have also been experimented into integration of BIM. Chen et al. (2020) proposed a framework to integrate the use of detailed look-ahead plans when applying BIM and RFID technologies, aiming at enhancing supply chain visibility and material flow process in pursuit of Industry 4.0. However, despite of the potentials to integrate the tracking method into BIM, the framework has only been implemented on simulated projects, and the benefits from the real-world projects have not yet been investigated.

Furthermore, Yang et al. (2020) developed an automatic monitoring system connecting workers and their associated tools for pair checking by using Wi-Fi networks on construction sites. The study demonstrated high potential of using radio-based technology to enable near real-time detection of interaction of workers and tools. Their research was conducted only as a lab test and was focused on construction safety. They did not consider production flows or operations in their study.

Compared to other radio-based tracking solutions, the BLE tracking method has the following characteristics and advantages for indoor monitoring of multiple resources in parallel: 1) the BLE tracking method involves minimal false negative alerts and requires the least input of infrastructure and time for calibration (Park et al., 2016); 2) the solution is cost efficient and lightweight for passive monitoring in previously tested construction projects (Zhao et al., 2019); 3) the solution supports multiple resource tracking with reliable identity information, which is important in workers' material handling. The BLE tracking method thus can be a suitable approach for tracking both labor and material flows for the purpose of improving material handling and evaluating a specific material management solution on-site. To the best of our knowledge, no reported studies to date have used the BLE tracking method within building projects' indoor environments to investigate the interactions of construction workers and materials.

Linked Data and Semantic Web Technologies

Linked data is an approach in which the web is used to create links between data from different systems or sources. The use of linked data offers significant advantages to alleviate the problem of information heterogeneity. Using this approach, data is machine-readable, explicit, and linked to other external data sets and can in turn be linked to and from external data sets (Bizer et al., 2011). The four basic uses of linked data include 1) the use of Uniform Resource Identifiers (URIs) to name resources; 2) the use of Hypertext Transfer Protocol (HTTP) URIs to provide access to resources *via* the internet; 3) the provision of extra information about resources using various standards, including the Resource Description Framework (RDF) and RDF query languages such as SPARQL, when looking up URIs; and 4) the provision of links to related URIs to explore more related factors.

RDF is the critical technology involved in establishing the "web of data," where data is encoded in the form of "subject, predicate, object" triples (Bizer et al., 2011). These triples are statements with resources modeled as subjects with their associated properties and the value or object of the properties. RDF provides a graph structure in which users can look up any URI in an RDF graph over the web to retrieve additional information. Thus, each RDF triple is part of the global web of data, and each RDF triple can be used as a starting point to explore the data space.

Increasing implementations of linked data have recently emerged in the construction domain. Construction information and data are often characterized as fragmented, since the construction information is usually acquired *via* various information sources and from different stakeholders who work in various construction disciplines and use a variety of tools, systems, and software. For example, Pauwels et al. (2015) reviewed various applications of linked data in the architecture, engineering, and construction (AEC) domain and concluded that linked data was used to improve information interoperability and to link across domains to fuse construction information for further information utilization. Curry et al. (2013) explored the use of the linked data approach to integrate cross-domain building data in order to serve a holistic database for the building lifecycle. Lee et al. (2016) proposed a linked data framework to share construction defect information to integrate the defect data from different silos to alleviate insufficient defect data sharing. To our knowledge, however, no recent works have used the linked data approach to integrate indoor positioning and scheduling information to support the investigation of on-site material and labor interactions.

Possibilities for the Tracking of Kits and Workers in Production Flow Improvement

Material handling in construction is still frequently reviewed as primitive, and advanced on-site material management practice is necessary for improvement (Caldas et al., 2006). Site material management could substantially benefit from automated tracking technology and automation in detection (Grau et al., 2009). For example, the use of material tracking practice could enhance worker productivity (Nasir et al., 2010) and minimize the time workers spend on searching for the right materials (Gurmu, 2019). In particular, material tracking may be used to evaluate and improve logistics practice: a material kitting solution which was proposed to enhance the time efficiency (Hanson and Medbo, 2012).

Specifically, the kitting solution in logistics allows for more efficient and prompt material deliveries directly to work locations. With origins in manufacturing industries, the concept of kitting involves packing and delivering the products necessary for an assembly task into one single package to a designated workplace (Bozer and McGinnis, 1992). Because kits can be delivered close to the exact work locations, the practice can enhance productivity by allowing for more efficient material usage in work locations and reducing the time spent looking for components required for various tasks (Tetik et al., 2020), thus contributing to overall work progress and production stability. But the relationship between material storage and project productivity has not been examined thoroughly in construction logistics (Seppänen and Peltokorpi, 2016). Kitting is usually used with other logistics practices such as logistics hubs and just-in-time (JIT) delivery. Logistics hubs can be configured to support assembly and kitting activities (Hamzeh et al., 2007). Tetik et al. (2020) showed, using four case studies, that a kitting intervention could stabilize assembly work and increase workers' productivity and workplace utilization. They measured work performance *via* schedule compliance, the share of value-adding time in work locations, and labor productivity by applying the camera-based video monitoring (for 44 days in total) and manual observation (for 25 days in total) methods of data collection. While their research did demonstrate the value of kits, their research method was resource intensive and may not be implemented scalably by practitioners who wish to improve their logistics practices. The management of kitting still encounters potential challenges because no automated way currently exists to calculate key performance indicators (KPIs), which are used to evaluate the success of the kitting method. Therefore, the benefits often remain anecdotal, which may hinder the implementation of such systems.

In the current paper, we first explain the indoor positioning system infrastructure and a case in which a kitting logistics solution was used; we then develop a linked data framework to connect the typically heterogeneous information sources of labor, materials, and schedules. Next a novel method is proposed to calculate the time-matching level of workers and materials in work locations based on their detected uninterrupted presence. Finally, new KPIs are introduced to evaluate the kitting practice for the improvement of site material management and work progress in construction.

METHODS

We follow the design science research methodology in this study (Peffers et al., 2007) and will demonstrate our research method in terms of system infrastructure, case description, time-matching level calculations, and the proposed linked data framework.

The real-time tracking system that was used in previous research (Zhao et al., 2019) was implemented in this case, but we expanded our focus into the integration of labor and material tracking in work locations using a kit-based logistic solution. The underlying kitting solution, as part of the material management practice, can be assessed based on the "uninterrupted presence levels" of workers, as captured by the tracking system. A worker's uninterrupted presence level is an uninterrupted period that the worker spends in the same work location before moving to another location. A threshold is set to define how much time workers need to stay at one work location before their jobs are considered uninterrupted (Zhao et al., 2019). For system implementation, we followed the process of a BLE-based real-time tracking system from a previous study (Zhao et al., 2019), including 1) setting up the real-time tracking system based on site floor plans, 2) evaluating the system accuracy by comparing the system results to a researcher's known movements (ground-truth data), 3) verifying the coverage of the system based on ground-truth data, and 4) capturing and analyzing the uninterrupted presence of workers and material kits.

Next, the real-time tracking system architecture and model are demonstrated. Then our case study is introduced in more detail.

Real-Time Tracking System Infrastructure

Our current research uses the same BLE-based real-time tracking system that Zhao et al. (2019); Zhao et al. (2021) used in their previous study. In the model, BLE beacons were used that could be associated with construction workers who had previously agreed to be monitored. The beacons send their media access control (MAC) address to the gateways (Raspberry Pi) periodically at an approximately one second frequency; the gateways then transmit the information to the cloud. The information contains a unique MAC address of each beacon assigned to a worker's profile and a time interval for the worker's presence in the database. The data analyzer identifies the beacons' locations from the magnitude of the received signal strength indicator (RSSI). To solve the potential signal flickering problems (the gateways are close to each other, and the results that are detected flicker between locations (Zhao et al., 2019)), the system uses recent RSSI values; the oldest values are removed when new values are pushed in the data analyzer. The RSSI value is averaged and the outlier values minimized to mitigate potential flickering interference. When a worker moves from one location to another and is detected by a different gateway, a new time interval is automatically generated in the system. The cloud provides downloadable data for future analysis. The architecture of the indoor tracking application used in our case studies is illustrated in **Figure 1** (Zhao et al., 2019).

Case Description

The case a renovation project was selected in Helsinki, Finland. The renovation work was undertaken in a three-floor building during June 2018. The case project team applied a kitting logistics solution because of the potential to improve workplace utilization rates by minimizing the wasted efforts of material transportation from storage areas to the site (Tetik et al., 2020). We placed one gateway in each apartment, with nine total installed gateways (eight gateways in eight apartments and one at the entry on the ground floor). Eight workers (including carpenters, plumbers, plasterers, and bricklayers) agreed to be monitored and were given the beacons; each of the eight material kits was also attached

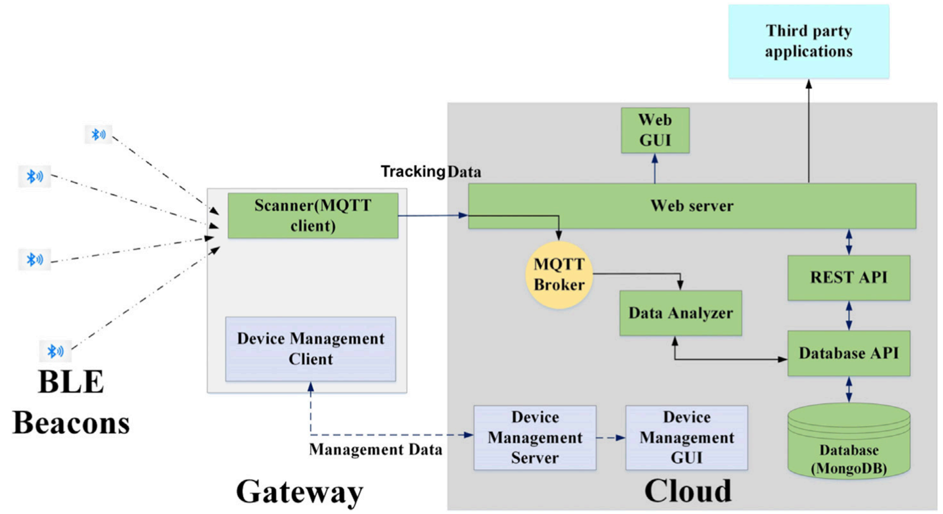

FIGURE 1 | The architecture of the tracking system applied in our case studies (adapted from Zhao et al., 2019).

with beacon tags for monitoring. Due to the different sizes of the apartments, the quantities of materials in the kits could be different, but the materials were the same for the tracked tasks in each apartment. Each material kit was assigned to each apartment for the tasks shown in **Table 2**. As shown in the table, each kit included the necessary material for the bathroom renovation in that specific apartment. The possibility of attaching both material and labor data enabled us to monitor the interactions of workers as they went about their on-site material-related tasks.

Figure 2 shows a simplified floor plan, with gateways marked in the jobsite. **Table 2** shows a task schedule summary for tracked workers and tasks. Each tracked task follows the same sequence from apartment A3 to A4, A8, A7, A1, A2, A6, and A5. Each successor apartment in the sequence for the same task is always scheduled half a day later than the former apartment, skipping weekends. The scheduled worktime is from 7:00 to 11:00 in the morning for the first half day, and from 11:30 to 15:30 in the afternoon for the second half day. The tasks listed in the table only covered work that was done in bathrooms. Workers from other trades (such as electricians and painters) were on the site during the tracking period in the workflow, but we did not monitor their tasks.

System Coverage and Accuracy

To ensure the quality of the results, we needed to first test the accuracy and coverage of the tracking system. The definition of "accuracy" and "coverage" from previous research (Zhao et al., 2019) was followed: accuracy is defined as the proportion of how much time, detected by the system, is recorded in the correct location and at the correct time, while coverage is defined as the share of the total time detected by any gateway of the system. For any incorrectly detected times recorded in the system, we classified these times into three non-match categories (Zhao et al., 2019): 1) non-match category 1 (the beacons detected by an incorrect gateway for a period of over a minute); 2) non-match category 2 (data flickering issue, the beacons detected by gateways that were near each other); and 3) non-match category 3 (the beacons that were not detected at all due to coverage problems.

The system accuracy and coverage were evaluated by comparing the tracking results with ground-truth data (Zhao et al., 2019). We had a researcher simulate workers' possible job routines on-site in both cases. The researcher self-recorded his movements to serve as the ground-truth data. **Table 3** presents a summary of the system accuracy and coverage results in this case. Compared to previous renovation project tracking in which the system reached 71% coverage and 55% accuracy *via* the same tracking method, with gateways installed at stairwells on each floor (Zhao et al., 2019), our tracking data achieved sufficient system accuracy without sacrificing coverage, mainly because we placed gateways in each apartment near the bathroom area where the material-related work was scheduled in this renovation project. This placement decreased the interference compared to the previously reported case, where gateways on adjacent floors could interfere with each other and cause detection inaccuracies.

Linked Data Framework

The proposed framework is designed to provide automatic identification of labor and material KPIs with limited human disturbance in order to support stakeholders in understanding the situation of on-site operations (see **Figure 3**). The framework also connects the database of indoor positioning data with external data sources such as schedules. Three tracks have been designed in this framework, including Data collecting, Linked data implementing, and Data processing. The Data collecting is the initial track that obtains the indoor positioning tracking data of the labor and material kits, as described in *Real-Time Tracking System Infrastructure section*—the real-time tracking system infrastructure and project scheduling data. Following the data collecting track, the Linked data implementing track triggers. The major objective of this track is to prepare, convert, and link the data collected from the indoor positioning system and

TABLE 2 | Task schedule summary for tracked workers and tasks.

Worker type	Tasks	If using materials, included in the kits?	05-31 07:00 05-31 11:00	05-31 11:30 05-31 15:30	06-01 07:00 06-01 11:00	06-01 11:30 06-01 15:30	06-04 07:00 06-04 11:00	06-04 11:30 06-04 15:30	06-05 07:00 06-05 11:00	06-05 11:30 06-05 15:30	06-06 07:00 06-06 11:00	06-06 11:30 06-06 15:30	06-07 07:00 06-07 11:00	06-07 11:30 06-07 15:30	06-08 07:00 06-08 11:00
1	1	Yes	A3	A4	A8	A7	A1	A2	A6	A5					
2	6	Yes		A3	A4	A8	A7	A1	A2	A6	A5				
2	7	Yes			A3	A4	A8	A7	A1	A2	A6	A5			
2	8	No				A3	A4	A8	A7	A1	A2	A6	A5		
3	9	Yes						A3	A4	A8	A7	A1	A2	A6	A5
4	12	No							A3	A4	A8	A7	A1	A2	A6
1	2	Yes											A3	A4	A8
1	3	Yes												A3	A4
			06-08 07:00 06-08 11:00	06-08 11:30 06-08 15:30	06-11 07:00 06-11 11:00	06-11 11:30 06-11 15:30	06-12 07:00 06-12 11:00	06-12 11:30 06-12 15:30	06-13 07:00 06-13 11:00	06-13 11:30 06-13 15:30	06-14 07:00 06-14 11:00	06-14 11:30 06-14 15:30	06-15 07:00 06-15 11:00	06-15 11:30 06-15 15:30	06-18 07:00 06-18 11:00
3	9	Yes	A5												
4	12	No	A6	A5											
1	2	Yes	A8	A7	A1	A2	A6	A5							
1	3	Yes	A4	A8	A7	A1	A2	A6	A5						
1	4	Yes		A3	A4	A8	A7	A1	A2						
1	5	Yes			A3	A4	A8	A7	A1	A2	A6	A5			
4	13	Yes				A3	A4	A8	A7	A1	A2	A6	A5		
3	10	Yes										A3	A4	A8	A7
4	14	Yes												A3	A4
			06-18 07:00 06-18 11:00	06-18 11:30 06-18 15:30	06-19 07:00 06-19 11:00	06-19 11:30 06-19 15:30	06-20 07:00 06-20 11:00	06-20 11:30 06-20 15:30	06-21 07:00 06-21 11:00	06-21 11:30 06-21 15:30	06-22 07:00 06-22 11:00	06-22 11:30 06-22 15:30	06-25 07:00 06-25 11:00	06-25 11:30 06-25 15:30	06-26 07:00 06-26 11:00
3	10	Yes	A7	A1	A2	A6	A5								
4	14	Yes	A4	A8	A7	A1	A2	A6	A5						
4	15	Yes			A3	A4	A8	A7	A1	A2	A6	A5			
3	11	Yes				A3	A4	A8	A7	A1	A2	A6	A5		
4	16	Yes						A3	A4	A8	A7	A1	A2	A6	A5

WORKER TYPES: 1 (bricklayers), 2 (plasterers), 3 (plumbers), 4 (carpenters). TASKS: 1 (door wall masonry), 2 (rebar mesh), 3 (floor concreting and draining), 4 (surface priming), 5 (waterproofing rolling), 6 (wall priming), 7 (plastering), 8 (cleaning), 9 (drainage), 10 (pipe attaching and connections), 11 (toilet installation and connection), 12 (layout), 13 (frame installation), 14 (suspended ceiling plating), 15 (shower wall fixing), 16 (applying silicone in walls).

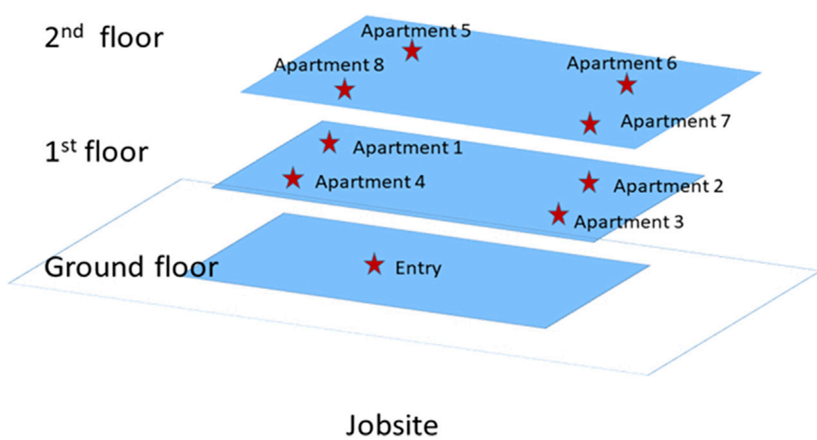

FIGURE 2 | A simplified floor plan, with gateways marked on-site.

TABLE 3 | Summary of system accuracy and coverage (all times in minutes).

Total simulation time on-site	Total matched time	Non-match category 1 time	Non-match category 2 time	Non-match category 3 time	Accuracy (%)	Coverage (%)
214.2	189.4 (88.4%)	14.6 (6.8%)	4 (1.9%)	6.2 (2.9%)	88.4	97.1

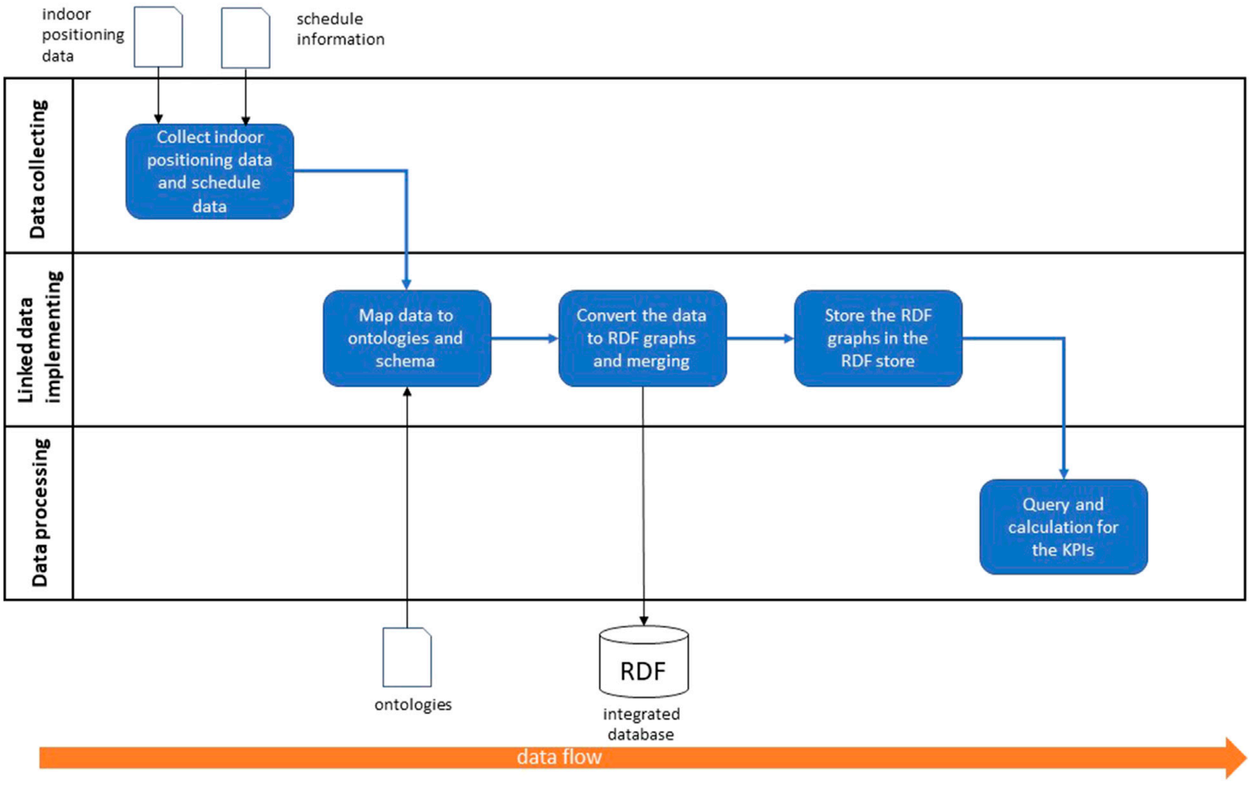

FIGURE 3 | Architecture of the linked data framework.

schedules, based on the linked data method, to create an integrated database that holds the comprehensive indoor positioning data and scheduling data. In this track, as a first step, the indoor positioning data of the tracking labor and material kits collected from the indoor positioning system and the project schedule is mapped in a certain ontology and schema for formalizing and creating the interlinks. The data is then converted into RDF graphs and stored in the RDF graph store. The final track is the Data processing, in which the integrated RDF graph is processed and queried to calculate the KPIs of workers' overlapping time levels and material kits based on the principles introduced in the following part.

Calculation of Workers' Time-Matching Levels and Material Kits in One Apartment

Since kitting material logistic solutions require each material kit to be delivered directly to each work location (in this case, each apartment bathroom), workers' time-matching levels and material kits can be used to indicate how well the underlying kitting solution has worked and whether the workers were able to use materials from the kits to conduct their tasks in various work locations. The workers' time-matching levels and kits refer to the time period when workers' detected presences overlap with the kits' detected presences.

Workers and material kits at one work location can have the following interactions: 1) both the material kit and workers are in the work location; 2) the material kit is in the work location, but the worker is not; 3) the worker is in the work location, but the material kit is not; and 4) neither the material kit nor the worker is in the work location. Scenario (1) is the best scenario when a worker is scheduled to perform the material-related tasks at that location, while scenarios (3) and (4) could indicate issues with the kitting solution because workers are working without the kit, or material kits have not been delivered as planned.

The raw data was analyzed to estimate the overlapping time level of workers and material kits for each apartment using the following steps.

1) The uninterrupted presence threshold represents the minimum time period that a worker needs to be present at one site location without interruption gaps to be able to count this presence as uninterrupted (Zhao et al., 2019). We set this threshold for 10 min as the highest-tested value in Zhao et al.'s work (2019) because we wanted to focus on longer continuous working periods rather than brief visits in a location. Because we installed one gateway in each apartment in the building, we were able to classify all detected uninterrupted worker presences by each work location (in this case, each apartment). The threshold was not applied on material kits because, due to their weight and immobility, their location is more fixed, and filtering out short visits is not required.
2) For a single apartment, we aggregated all detected presences of the material kit assigned to that apartment. For example, in apartment 1, we searched for all detected presences of the material kit assigned for apartment 1.
3) T1 = the uninterrupted presence of a worker during the same time when the material kit for that assigned apartment was present.
4) T2 = the uninterrupted presence of a worker matched the time period of a material kit that was assigned to other apartments but was present in the current apartment.
5) T3 = the uninterrupted presence of a worker that did not fall into time periods of any material in that apartment (the uninterrupted presence of the worker thus = $T1 + T2 + T3$).
6) T4 = the operational time of each worker, which was defined as the time from a worker's first detected time of the day to the last detected time of the day (Zhao et al., 2019).
7) The presence index (Zhao et al., 2019) = $\frac{\mathrm{T1+T2+T3}}{T4}$.
8) The time-matching level of workers and materials in one apartment was then estimated by comparing T1, T2, T3, and T4 and their ratios:
   - TMD (time matching for designated) = $\frac{T1}{\mathrm{T1+T2+T3}}$, indicating the optimum scenario of a worker and the correct material kit in the apartment.
   - TMA (time matching for any) = $\frac{T1+T2}{\mathrm{T1+T2+T3}}$, indicating the presence of a worker together with any material kit in that apartment.
   - NM (no material) = $\frac{T3}{\mathrm{T1+T2+T3}}$, indicating the share of time when the worker was present in the location without any material kits.
9) Next, we followed the linked data framework, with the aim of connecting the indoor positioning data with the external scheduling information to enable further actual and as-planned comparisons of KPI calculations:

$$\text{STMD (scheduled time matching for designated)} = \frac{\text{time when workers have the assigned material under their task schedules}}{\text{uninterrupted presences of workers}}$$

$$\text{STMM (scheduled time matching for material)} = \frac{\text{time when the material kit is in the assigned apartment under task schedule}}{\text{accumulative task schedule in that apartment}}$$

Figure 4 shows how the STMD and STMM calculations were carried out based on detected presences and scheduling information.

In addition to calculating the time-matching level of workers and material kits, we were also interested in the following metrics related to the time and movements of material kits to evaluate the performance of the logistics system: 1) delivery times of the kits to the first detected apartment on-site; 2) removal times of the kits from the last detected apartment on-site; 3) number of times each kit moved between the delivery time and removal time. Those metrics contribute to understanding in more details of the material flows such as waiting time and the level of unnecessary inventory. Although these metrics are not new, the novelty of the method lies in using the proposed lightweight monitoring system to obtain the time and location information automatically and passively to analyze these metrics without time consuming data collection efforts.

In summary, together with comparing the time-matching level of workers and material kits based on their overlapping uninterrupted presence, kit delivery times, and movements based on the analyses of automatically detected temporal and spatial information by the real-time tracking system, we were able to assess the soundness of the kitting solution in this case, such as by examining how well the kitting material management practice worked in each work location.

Implementation of the Linked Data Framework

Our aim was to establish and develop an automated process of data analysis modeling where the tracking data of cross-type resources such as materials and labors, together with workers' schedules, could be linked and integrated into one proposed framework. Based on the architecture discussed in the Method section, we then implemented the linked data framework for the case study (**Figure 5**).

Ontology Selection and Mapping

A standard data structure was used as the basis for formalizing and integrating the indoor positioning data. In this research, we used the extension of digital construction ontologies (Törmä and Zheng, 2020), or DiCon, for the logistics structure (Zheng et al., 2020). DiCon is a set of ontologies that may be used to define the basic terminologies and relations of the digitalized construction process. DiCon is also used to model and represent the digitalized information obtained from the implementation of information and communication technologies (ICTs) in the construction domain. Using DiCon, we used classes including "person," "batches," "location," "sensors," and "events" and their interrelations to represent the indoor position data in this case. In the DiCon logistics extension, the "material kit" is defined to represent material kits, which are groups of material batches. The mapping of the data to DiCon and logistics is shown in **Figure 6**. For the scheduling data, the information of every task and its assigned location and labor

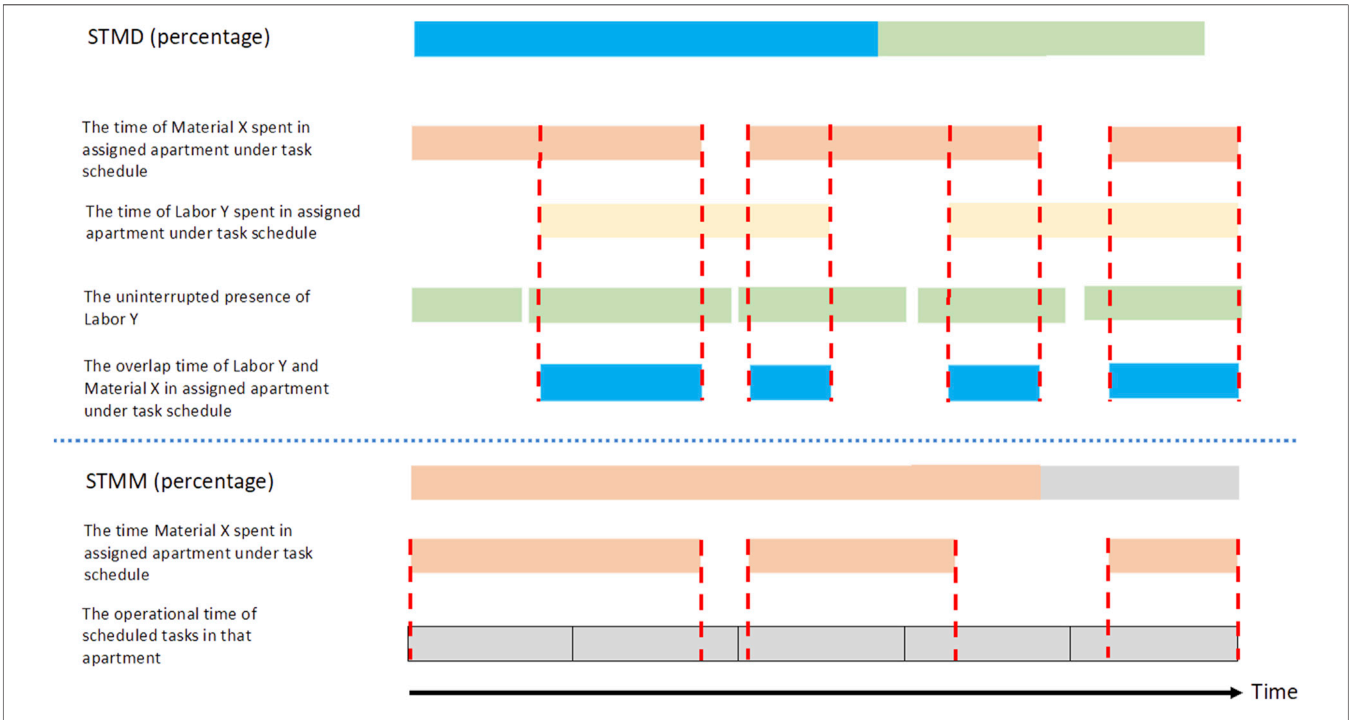

FIGURE 4 | STMD and STMM calculation demonstration.

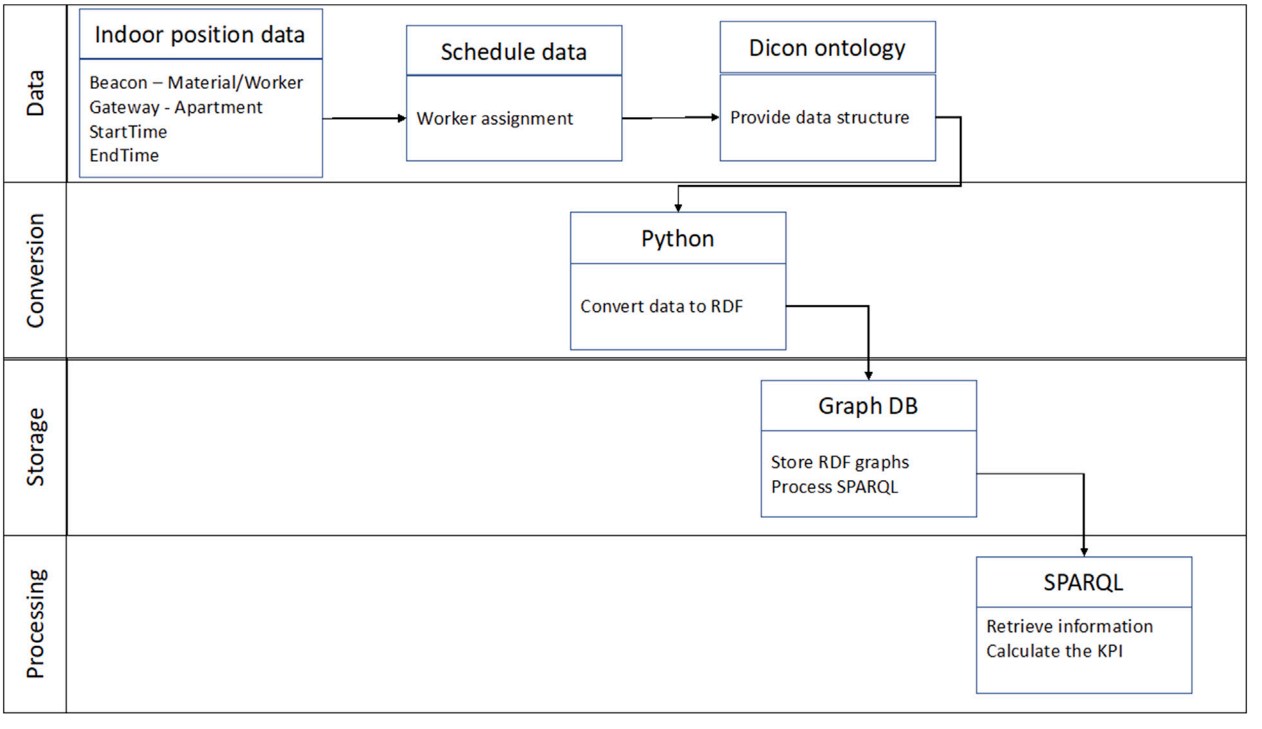

FIGURE 5 | Detailed process of linked data framework implementation.

can also be represented based on DiCon. Every record of the indoor positioning system is considered to be an "event," which is observed by a beacon and a gateway during a time interval when the gateway captures the signal from the beacon. Both beacons and gateways are considered to be sensors where beacons are hosted by workers and material, which are known as the instance

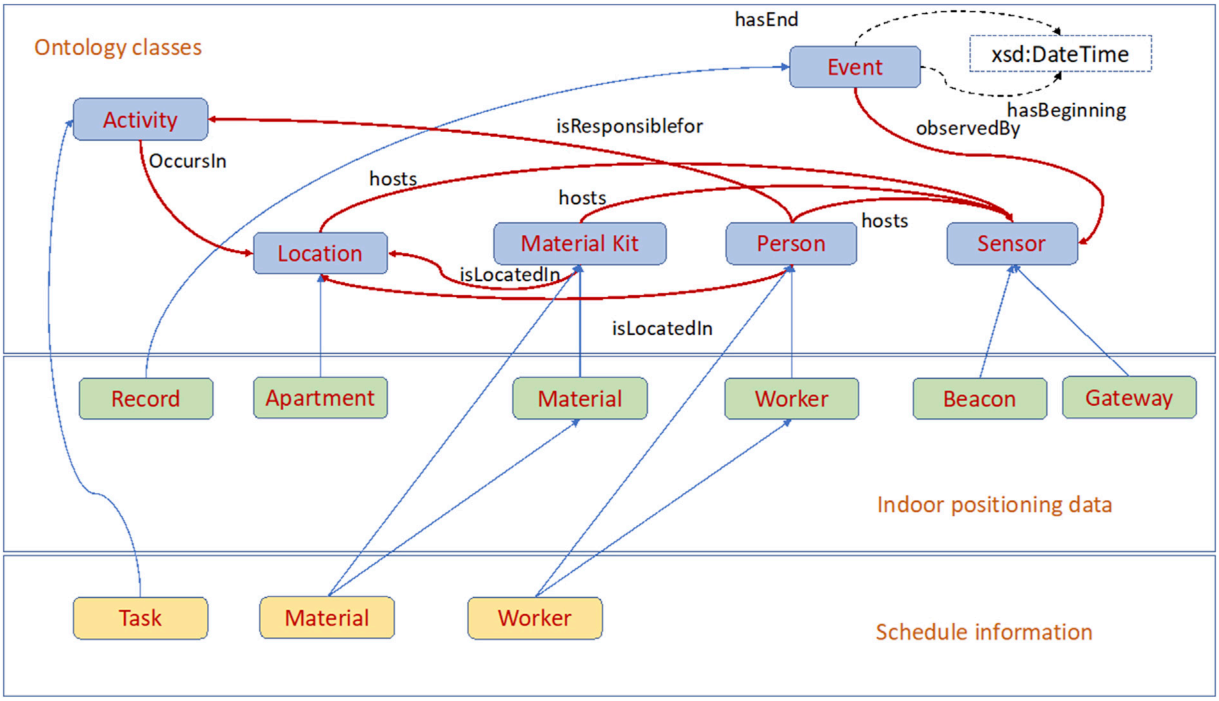

FIGURE 6 | Mapping the indoor position data to DiCon.

of "person" and "material kit" classes in the DiCon logistics extension. The gateways are hosted by apartment, which is a "location."

Data Conversion and Storage

In order to establish the linked data for further data processing, the data and information obtained from the indoor positioning system and project schedule must be converted from tabular format in a spreadsheet into RDF format based on the previous result of ontology mapping. To achieve the conversion, in this case, a Python script was developed by utilizing an open source Python library called RDFlib (2009) to handle the conversion process.

After the conversion, the RDF graphs were generated and stored in the Graph DB store. Graph DB is among the most popular RDF stores for storing and managing semantic information serialized in RDF format. In the Graph DB environment, users can also conduct SPARQL queries to process, search, and retrieve information from the database.

After the implementation of the linked data framework, we then conducted data analysis on material flows and time-matching levels of workers and kits, with the aim of calculating the material-related metrics introduced in the Method section.

RESULTS

Material Flows

Figure 7 shows an example of one material kit (assigned for apartment A7) that was moved inside the building during the tracking period. The material kit was first detected at apartment A7 at 07:03 on June 1. The material kit was then moved to apartment A2 at 17:04 on June 17 and subsequently moved to apartment A1 at 11:04 on June 22. Finally, the kit was moved to the entry area of the building at 08:20 on June 26. **Table 4** provides a summary of the moving times of each material kit with its delivery and removal times on-site, in addition to the schedules of task start and end times in the respective apartments. Because the presence of the material kit for apartment A3 was not found in the system due to the loss of the beacon attached to the kit, we decided to exclude apartment A3 from the analysis.

Out of a total of seven material kits, six were delivered on-site earlier than required (the first task scheduled in the apartment), and six were removed from the site later than required (the last task scheduled in the apartment). On average, kits were moved 6.9 times between apartments. The average number of move times for the cases where kits were delivered earlier than required (apartments 1, 2, 5, 6, 7, and 8) was 6.6, lower than for the kit that was delivered later than required (apartment 4), which was moved 8 times. In our case, the delays of material kits delivered later than the first tasks scheduled led to more movement of kits between apartments on average. It should be noted that if the kitting solution had worked perfectly, no movements between apartments would have occurred.

For the task schedule in apartment A7, the material kit for apartment A7 was moved away from apartment A7 at 12:43 on June 17, but the scheduled end time of the last task in that apartment was at 11:30 on June 22. However, after the material kit

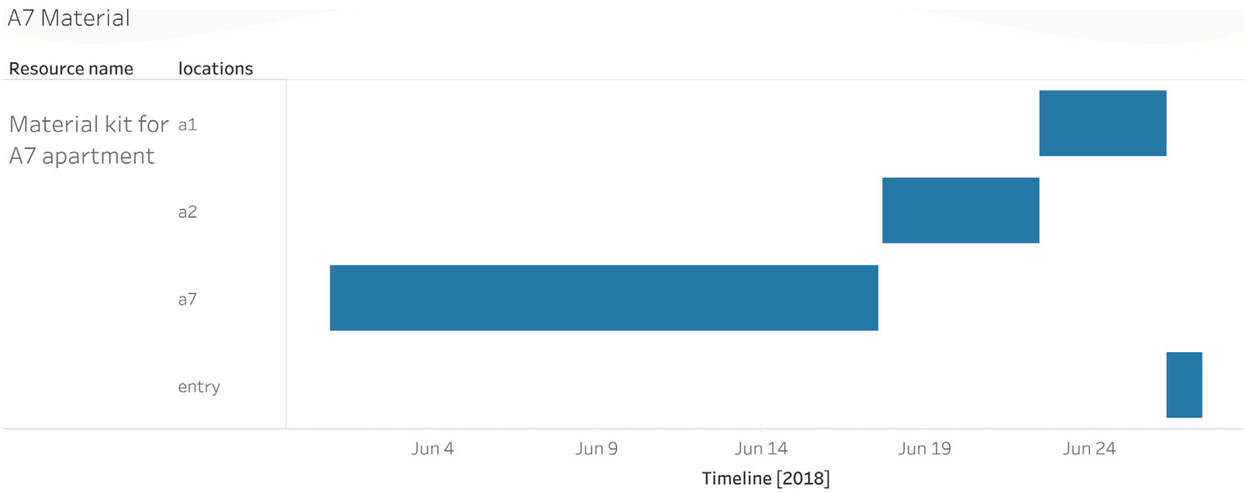

FIGURE 7 | Material flow of the material kit for apartment A7 inside the building.

TABLE 4 | Moved times between apartments for each material kit.

Material kit for each apartment	Moved times between apts. During tracking	Kit delivery times when detected 1st time	Kit removal times when detected last time	Schedule for start time of 1st task in (apt. #)	Schedule for end time of last task in (apt. #)
A1 kit for apartment 1	5	26-05-2018 17:20	26-06-2018 11:57	04-06-2018 07:00 (1)	22-06-2018 15:30 (1)
A2 kit for apartment 2	8	28-05-2018 13:14	25-06-2018 07:30	04-06-2018 11:30 (2)	25-06-2018 11:30 (2)
A4 kit for apartment 4	8	31-05-2018 16:50	01-07-2018 19:14	31-05-2018 11:30 (4)	21-06-2018 11:00 (4)
A5 kit for apartment 5	7	30-05-2018 11:36	27-06-2018 12:47	05-06-2018 11:30 (5)	26-06-2018 11:30 (5)
A6 kit for apartment 6	5	31-05-2018 09:22	27-06-2018 19:10	05-06-2018 07:00 (6)	25-06-2018 15:30 (6)
A7 kit for apartment 7	3	01-06-2018 07:03	27-06-2018 10:55	01-06-2018 11:30 (7)	22-06-2018 11:30 (7)
A8 kit for apartment 8	12	31-05-2018 09:09	29-06-2018 10:01	01-06-2018 07:00 (8)	21-06-2018 15:30 (8)
Average	6.9				

for A7 was moved away, the material kit for A4 was moved to apartment A7 from June 18 to June 21, which covered the remaining time for tasks required in the apartment.

The material kit for A7 was observed in apartment A1 from June 22 to June 26, which covered the remaining time for tasks required in apartment A1 after the material kit for A1 had already been moved away, at 12:28 on June 18. These kit movements showed that the implementation of the kitting process encountered problems during this project because the originally assigned kit could not be used to complete the work.

Time-Matching Level of Labor and Materials in the Apartment

Next, we calculated how the material flow interacted with the location information of workers in the apartment. Due to space limitations, we have visualized the results of only one apartment (apartment A7), and we present the results of the whole data set in a later section. **Figure 8** shows a visualization of the carpenter in apartment A7, while the material kits for A4 and A7 were detected as being present during the same tracking period of June 1 to 21. **Figure 8** also shows that the worker was mostly present throughout the same time range as the material kit for A7 in that apartment, except for his or her presence from June 18 to 21, when the material kit for A7 was undetected while the material kit for A4 was present. Because the task of suspended ceiling plating was scheduled in apartment A7 starting on the afternoon of June 18, the worker could have taken the suspended ceiling plates from the material kit assigned for apartment A4 instead.

Table 5 summarizes the TMD, TMA, and NM results for carpenter one and how these values were calculated in apartment A7. Because we set the threshold of an uninterrupted presence for workers at 10 min, all time intervals from workers that are shorter than 10 min were omitted from the analysis. The 11.1% of NM time of the assigned worker (carpenter 1) with material presence represents time in which the worker was detected in the apartment without any material kits being around. A few possible reasons for this situation are as follows.

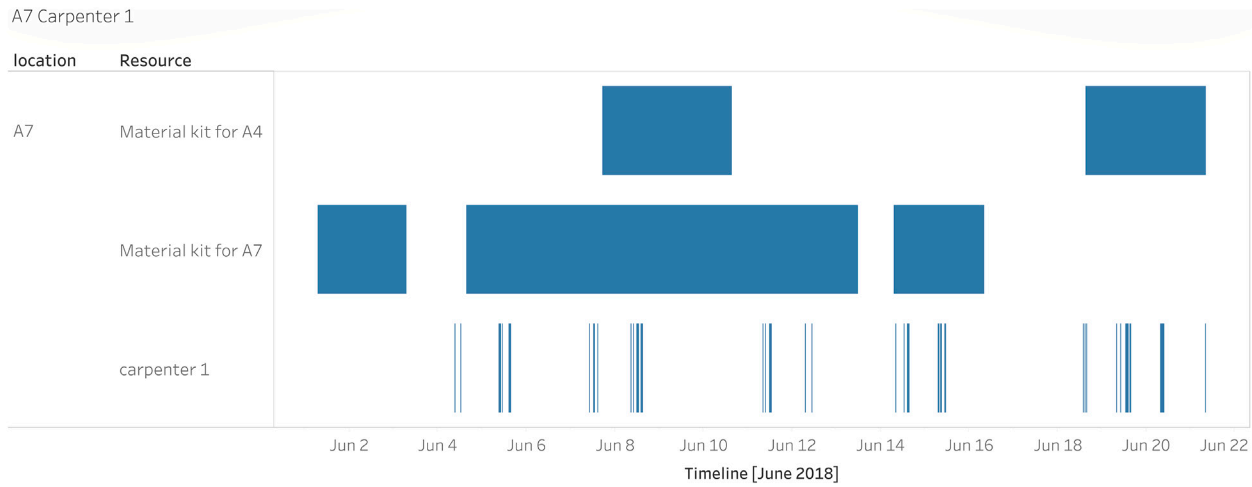

FIGURE 8 | Movement visualization of carpenter 1 with material kits in apartment A7.

TABLE 5 | TMD, TMA, and NM results for carpenter one in apartment seven.

Metrics	Calculation	Results
T4		2,794 min
T1		242 min
T2		58 min
T3		30 min
Presence index	(T1+T2+T3)/T4	11.8%
TMD	T1/(T1+T2+T3)	73.4%
TMA	(T1+T2)/(T1+T2+T3)	88.9%
NM	1-TMA	11.1%

TABLE 6 | Summary of the time-matching levels in all apartments (all numbers in minutes except percentages).

Apartment	T1	T2	T3	TMD (%)	TMA (%)	NM (%)
1	3,534	47	20	98.1	99.4	0.6
2	2,225	383	236	78.2	91.7	8.3
4	604	18	46	90.4	93.2	6.8
5	283	81	126	57.8	74.3	25.7
6	620	117	231	64.0	76.1	23.9
7	1,432	363	193	72.0	90.3	9.7
8	181	9	73	68.7	72.1	27.9
Sum	8,879	1,018	925	82.0	91.5	8.5
SD	1,140	148	83	13.3	10.0	10.0

1) The worker was waiting for the material.
2) The worker had to retrieve the material from other places (or parts of other kits) and then returned to do the work.
3) Materials were delivered as supplemental orders and were not included in the original kits.
4) The worker could have been with the material kit for apartment A3, since the movement of that kit remained unknown due to the loss of the beacon for that kit.
5) The material kit was incorrectly detected (for example, because of flickering between apartments). This impact was minimal, however, because during manual investigation of the time period between June 1 and 27, from the kit being delivered to the site until its removal, we noted that only 4.33 min of flickering (detection in different apartments) occurred. Although the exact activities of the worker during this time were unknown, the first three points could be regarded as an indication of problems in the kitting process. In addition, we noted two time gaps in the material kit for apartment A7, between June 3 and 4 and between June 13 and 14. During these times, the material kit for apartment A7 was found in A3: from 11:06 on June 3 to 6:54 on June 4, and from 15:34 on June 13 to 7:10 on June 14.

Evaluation of the Time-Matching Level in all Tracked Locations and for Different Tracked Workers

To determine whether the tracking of material kits and labor together would add more insightful information to the evaluation of the kitting solution on-site, we then calculated and summarized the metrics, grouped by location and workers (see **Tables 6** and **7**).

Overall, 8.5% of the total uninterrupted presence of all workers (925 min) represented the time when the workers were present either with the A3 kit or with no material kits in the same apartment. In addition, 18% of the total uninterrupted presences (1,943 min) represented the time when the workers were present without material kits designated for the underlying apartments. The standard deviation (SD) of all apartments (except apartment 3) was 10%, so we noted some locations where the kitting process worked better (i.e., with a low NM value, for example 0.6% in apartment 1) and some locations where workers were not using the kits for a large portion of time (for example apartment 8, with 27.9%).

TABLE 7 | Summary of the time-matching levels for each individual worker (all numbers in minutes except percentages).

Workers	Operational time	T1	T2	T3	Presence index (%)	TMD (%)	TMA (%)	NM (%)
Bricklayer 1	10,375	1,111	381	125	15.6	68.7	92.3	7.7
Bricklayer 2	9,539	1,785	82	93	20.5	91.1	95.2	4.8
Carpenter 1	10,938	1,135	160	209	13.7	75.5	86.1	13.9
Carpenter 2	9,391	1,107	102	193	14.9	78.9	86.3	13.7
Plasterer 1	5,737	937	85	42	18.6	88.0	96.0	4.0
Plasterer 2	6,815	1,089	98	103	18.9	84.4	92.0	8.0
Plumber 1	6,117	723	34	112	14.2	83.2	87.1	12.9
Plumber 2	6,793	993	75	48	16.4	89.0	95.7	4.3
Sum/mean	65,705	8,879	1,018	925	16.5	82.0	91.5	8.5
SD	1,928	285	101	56	2.3	7.1	4.0	4.0

Next, the time-matching level based on individual workers throughout their operations in all work locations was evaluated (**Table 7**).

For the individual workers, the SD values for NM were much smaller than for the locations. The problems with kitting seemed to occur mostly with carpenters, while other trades showed smaller NM values. The carpenters were scheduled to do the non-material-related task (layout) first, and then to start using the materials in the kit; therefore they may have been in work locations before the kits had arrived, thus leaving larger NM values compared to other crews. In addition, all workers were detected to have periods in the presence of material kits other than those that were designated, on average 9.4% of the time [T2/(T1 + T2 + T3)]. The results in **Table 7** show an estimate of how well the kitting solution worked for each tracked worker.

Estimation of Compliance With the Schedule

Next, SPARQL queries were used to calculate how well the uninterrupted presences of workers and material kits matched with the schedule. The proposed linked data framework was used to create an integrated RDF graph of the linked indoor positioning data and the scheduling information. This section presents an example of using SPARQL queries based on semantic logics and structured data to explore the worker and material kit interaction performance in compliance with the schedule. In the example, the "time matching for designated" (TMD) indices were further specified to investigate the compliance with the schedules. TMD was further addressed as the time-matching level of a worker's uninterrupted presence matching the material kit assigned to a specific apartment in compliance with the schedule ("scheduled time matching for designated" [STMD]). STMD was designed to identify the time of labor-material matching in the schedule-assigned work locations, while STMM was designed to investigate the spatial-temporal metric of the material kit in compliance with the schedule. Due to space limitations, the STMD of carpenter two in apartment seven and the STMM of the A7 material kit were selected as a case to illustrate the query process. The queries were conducted in the Graph DB environment. The results of the queries show the capability to flexibly process and retrieve meaningful information from organized indoor positioning data formed in RDF.

The first query is used to identify the uninterrupted presence of carpenter two in apartment 7 (T1 + T2 + T3) from the processed database, in which the uninterrupted presence threshold of 10 min had already been applied. The query could thus be directly conducted to find all the records of the uninterrupted presence of carpenter 2. In this query, the variables to be explored were "?duration." In SPARQL, SELECT is a reserved function for listing all the variable results of interest that satisfy the conditions from the WHERE section. The query follows the logic where a worker hosts a beacon first and then the beacon and gateway observe the event, which contains the temporal information of the presence duration. In this case, we specified apartment seven and carpenter 2 as an example.

The second query is used to find the total overlapping time of a worker with an apartment-assigned material kit and to check if the worker's presence is in the designated apartments of all scheduled activities of carpenter 2—in other words, to identify the T1 that fits the schedule. The query follows the logic of first searching material kits and worker temporal overlaps at designated apartments and then comparing the identified overlapping time to the scheduled operation time in that location. The logic of identifying the overlap and comparing the overlapping time with the schedule is based on Allen's interval algebra (Allen, 1983).

We conducted the third query to find the duration of the corresponding material kit localized in the assigned apartment that fit the schedule. Allen's interval algebra (Allen, 1983) was also used in this query to find the overlap time of the scheduled activity and material presence in the target apartment.

The results of the three queries were then further processed based on the principles defined in the Method section. The accumulated results from the first query represent the uninterrupted presence of carpenter two in apartment 7 (T1 + T2 + T3), which is 2,233.32 min. The accumulated results from the second query represent the total time of the labor and the designated material kit in compliance with the schedule, which is 228 min. By dividing the uninterrupted presence accumulated from the result of the first query, the STMD may be calculated as 10.21%. The accumulated results from the third query represent the total time of the material kit in the assigned apartment that matches the scheduled tasks in that location, which is 2,132.27 min. By dividing the total duration of the planned tasks (7,200 min) accumulated from the schedule, the STMM of the A7 material kit was calculated to be 29.61%.

As shown in the example, calculating the STMD and STMM is possible by integrating the indoor positioning data and the scheduling information. The results of the STMD and STMM values are an enrichment of the material-related KPIs, which can provide further information for site managers to evaluate how the underlying kitting solution has worked for a specific worker (e.g., carpenter 2) or the kit (e.g., the A7 material kit) against his or her schedule. The implementation of the linked data framework also provides an alternative for identifying the desired time-matching level of workers and material kits in construction operations with a more automated and flexible procedure.

To summarize the results, the following outcome based on the proposed methods and the real-time monitoring system was achieved: 1) calculated kit moving times inside the building and analysis of the material kit flows from the delivery to the site until the removal of the kits. 2) investigated in detail the time-matching level of labor and materials in apartments, providing insights and evaluation of the tested kitting solution. 3) estimated level of compliance with schedule by applying the proposed linked data framework to connect other external available data sources. Next, the discussion was presented regarding the generalizability, reliability of the system, comparison to previous studies, contribution to knowledge, implication and limitation as follows.

DISCUSSION

Generalizability of the Method and the Reliability of the System

Little research to date has focused on the combination of real-time tracking for labor and material in construction sites for the purposes of addressing material mishandling and evaluating kitting solutions. In a few previous empirical works, researchers have analyzed material tracking data to support better material handling and site-work performance, but the generalizability of their methods has varied. For instance, Grau et al. (2009) developed localization algorithms based on a combination of RFID and Global Positioning System (GPS) technologies to capture the time spent on activities directly related to tracked steel material components and to analyze the impact of the tracking application on steel erection productivity. Because GPS is unsuitable for indoor environments, however, the generalizability of this method is limited to the outdoors. Tetik et al. (2020) evaluated the applicability of kitting by comparing four projects with and without kitting solutions, with a focus on the impact of work performance and management requirements. While they showed that kitting solutions could improve product flow and work performance, our focus is on the effectiveness of an applied kitting solution by showing the variability of kit presences associated with workers in multiple work locations. Their method can be used to capture logistics performance on a more detailed level but is not scalable due to the manual analysis required. Our approach presents a scalable solution based on the uninterrupted presence of workers and kits in work locations that still enables the calculation of KPIs, which can be used to evaluate logistics performance.

Our case was an apartment renovation project where small locations (in this case apartment bathrooms) enclosed with walls were used for analysis. Due to the project type, the accuracy and coverage values were high. In earlier research, Bluetooth-based systems showed lower accuracy and coverage values in projects with large, open areas. Kitting as a logistics solution has often been implemented first on project types with small work areas, because kitting is mainly used to solve issues related to a lack of space (Corakci, 2008). Large open areas typically have better possibilities to store materials, and thus the benefits of kitting may not be so large.

Generalizability to other project types should be explored in future research. The current method depends on apartment-specific material kits delivered to each work location. This type of logistics enables easy tracking because tracking beacons are required only for each kit. Although the system could, in theory, be applied for other types of materials as well, each tracked material has associated costs in time. A typical construction site contains an enormous amount of materials, and tagging all materials is not always practical. We analyzed this kitting solution in particular because of its ability to easily map materials to locations and tasks and the low number of tracked elements required. Previous researchers who have investigated materials on worksites, such as Grau et al. (2009), have taken a similar approach by focusing on individual types of materials, although the individual materials in the kits are also of interest. In future studies, the current method could be applied on selected individual materials to determine if their movements differ from the movements of kits.

The reliability of the system depends on the following factors: 1) the tracking accuracy and coverage. In our case, the accuracy reached 88.4% and the coverage reached 97.1%, which indicated high overall tracking reliability of system. 2) system implementation and maintenance. The system depends on assurance of gateway connectivity, power availability, and on workers and material kits carrying beacons at all times. In our case the beacon for the A3 kit was unfortunately lost onsite, which affected the monitoring of A3 apartment.

In any case, based only on the movement of tracked material kits, knowing whether a specific material part in a kit has been utilized is difficult. In the future, we aim to test the performance of a kitting solution by focusing on the material utilization level. For instance, the tracking method could be supplemented by vision-based technology, such as by integrating a camera monitoring and indoor positioning system in the work location. By implementing both vision-based technology and indoor positioning, we would not need to monitor the videos all the time but could instead shift our focus to the time period when the KPIs (e.g., NM) are alerted during the kitting process.

Comparison to Project-Level Presence Indices of Previous Studies

The concept of project-level presence indices was first introduced by Zhao et al. (2019). Such indices indicate the percentage of workers' uninterrupted presences inside their daily accumulated operation times at the project level. This setup means that project-level indices only show workers' uninterrupted presence values and take all workers into account. By differentiating work locations and non-work locations, project-level indices require small amounts of context information but provide important indications such as estimates of the overall efficiency of the worksite based on the share of workers' actual presence levels throughout a project.

Compared with project-level presence indices, in the current paper the concept was expanded further by dividing indices into categories based on the time-matching of material kits. These material-related uninterrupted presence metrics include TMD, TMA, and NM, which also require tracking data from the material kits for each work location. A project-level presence index is a metric of operations flow at the project level. Therefore, the material-related uninterrupted presence uses the resource flows from both material and labor perspectives, which creates opportunities to evaluate the current material management practice (in this case, the kitting solution). For instance, in the current case, the overall project-level presence index was 16.5%, which was lower than in previous studies with the same threshold value (Zhao et al., 2019). The index also indicates that 83.5% of the time, the worker was either undetected inside the building or was detected at one location for less than 10 min. Additionally, in our case the tracked material kits were not always at the designated location, and the workers were not always present with the correct kit in the apartment.

The current research extends the research conducted by Zhao et al. (2019) by investigating also material flows which have not been addressed in their previous studies. Zhao et al. (2019) assessed an overall percentage of workers' uninterrupted presence level for all workers in the project during the tracking period. This kind of project-level indices cannot be used to understand root causes of problems to inform improvement interventions. The project-level presence indices reflect on the productivity level of the entire project but do not include connections to task schedule or other site data sources. The measurement of labor and material kit integrated uninterrupted presence creates some new and deeper analysis opportunities. The efficiency of the logistic system can be analyzed by looking at materials and labor together in connection with the schedule. For that purpose, our study introduces new material-related metrics which can be used to provide supplemental information on top of the project-level uninterrupted presence indices. Therefore, the key motivation of this research was to broaden the knowledge of previous studies toward material management practices.

Overall, presence indices, which also consider material flows, provide a deeper understanding of production performance than those indices that rely only on the tracking systems of workers' location. In addition to project-level presence indices, the several metrics can be used to evaluate the kitting logistics solution from the following perspectives.

1) Waiting or other non-value-adding time spent in work locations can be analyzed from time-matching levels between workers and material kits (TMA and NM). The smaller the NM (or larger the TMA) value, the lower time disparity of workers who lack any kits.
2) Success of having a correct kit in a work location can be analyzed from time-matching levels between workers and the material kits assigned to the specific apartment (TMD). A larger TMD value implies that the assigned material kit with planned material contents was more successfully adopted in practice. The difference between TMA and TMD (TMA-TMD) also suggests a time level where the kits assigned to other apartments were occupied in the apartment when the assigned kit was absent, thus indicating potential work that workers needed to use from other apartments' materials for the underlying apartment. The TMA value may indicate problems with the bill of materials used to assemble the kit and will likely rise as a result of incorrect quantities or kinds of materials in the kits.
3) Success of following the original work plan can be analyzed from time-matching levels between workers with material kits under their original schedules (STMD and STMM). Larger STMD or STMM values imply that workers are spending time with material kits in work locations following the original plans. This information could be particularly valuable in projects that use, for example, the takt production concept, where the schedule is committed and followed (Frandson and Tommelein, 2014).
4) Unnecessary inventory can be calculated from the detected delivery time of material kits compared with the time when the first task requires the material in that kit. The lower the time gap between these two times, the less waiting or delays of the material to be used will occur. Unnecessary inventory is one waste type related to materials, and kitting practice is typically planned to be JIT (Tetik et al., 2020; Tommelein and Li, 1999).
5) Wasted time for moving of materials can be analyzed from the moving times of material kits between work locations. With more detected moving times of material kits, workers unavoidably waste more time transporting kits to the required apartments. In an optimally working kitting process, only one movement of the kit to its location, and then one movement out, should occur once all materials have been consumed.

In summary, we argue that a well-performing kitting solution should have 1) high TMA and TMD values, 2) ideally little difference between TMA and TMD values, and 3) no kit movements between work locations. If scheduling information is taken into consideration, then a good performance should also require high STMD and STMM values with the least possible time gap between detected delivery times and task schedules required for the underlying material kits.

Contributions to Current Knowledge

In the current paper, we contribute to tracking methods in construction by developing and demonstrating a method to manage kit-based logistics management using an indoor real-time tracking system to monitor both material and worker flows.

More specifically, the tracking method is developed to integrate material kit and labor tracking for a kitting logistics solution in a scalable way by measuring the uninterrupted presences of both labor and material kits.

One of the specific contributions to the methods based on the presence of materials and workers in work locations is that the developed method does not require manual observation or watching through camera videos to understand the process. For example, using camera monitoring and manual observations, Tetik et al. (2020) pointed out that the effects of random factors may be large due to a relatively small data set. Our method does not rely on manual analysis and thus is scalable to large data sets, which will help to avoid random factors.

In addition to the methodological development, the contribution to construction management lies in the introduction and demonstration of several KPIs to evaluate the effectiveness of the kitting solution. When the kitting process works in an optimal way, it fulfills the following requirements: 1) kits only go to the right apartment, 2) kits only move in once and out once, and 3) workers are present in the planned work location with the correct kit. The results have shown that none of the requirements were met in the project we tested, so the implemented kitting practice was far from optimal. Calculating these KPIs in real time could allow management to find the root causes of problems and to continuously improve on material logistic solutions. Such a system could be seen as a digital twin of the logistics process and could drive improvement in the way that Sacks et al. (2020) proposed in their recent paper on digital twin construction.

In the current paper, the existing knowledge was also contributed on data linkages in construction projects by we investigating the labor-material interaction in compliance with operation schedules. By applying the linked data method, we introduced a novel approach to integrating heterogenous data from both positioning tracking and schedules. With our introduction of the linked data approach, the cross-type resource data in construction becomes linked and machine-readable, which provides easy utilization of semantics for KPI calculations and the ability to conduct analyses without fragmentary raw data processing. The integrated data enables the evaluation of the effectiveness of kitting solutions compared to the plans, which cannot be achieved by individual data streams alone.

Managerial Implications

This work has several managerial implications for operations management in construction based on the proposed tracking application framework. First, the proposed system and KPIs can help site managers to understand how well the applied kitting solution performs. For instance, the disparity from the optimal situation quantified by NM can be used to indicate the amount of time when workers are present without any materials. Managers can use the method and KPIs when reallocating working resources to those places where the kitting practice appears to have the most challenges. For example, our case apartment A8 was found to be the most complex work location with the highest NM and kit-moving times, which should urge the site managers in this case to pay special attention to the task progress in apartment A8. Faulty amounts or kinds of materials for that apartment likely explained these issues.

Second, for logistics providers, the automated detected timestamps of kit delivery and removal in/out from the work locations, and the value difference between TMA and TMD, can provide useful information about the correctness and punctuality of kit deliveries. If TMA is equal to TMD, then all assigned material kits have been correctly placed in the apartments, and no other material kits are needed for replacement. Logistics providers can use the information of kit delivery and removal to estimate approximate kit usage using cycle times in each work location. They can also estimate the right quantity and correct size of kits to be delivered to the assigned apartment. Based on real-time data logistics, providers can dynamically update kit delivery plans and executions to the site (Kalsaas et al., 2014).

Third, for task schedulers, the study will provide practical KPIs for evaluating and continuously improving their processes. STMD can be used to evaluate the compliance levels of workers with the assigned material kits in apartments, while STMM can be used to evaluate the share of time when the material kit is placed elsewhere under the task schedule.

In summary, our research has introduced these KPI metrics to enable real-time monitoring for detecting problems in kitting practices in work locations. These metrics can potentially benefit logistics providers, site managers, and schedule planners. Lean interventions should be undertaken accordingly if the problems appear to be continuous, as indicated by the KPIs.

The linked data method also provides the opportunity to align heterogenous data sets from various domains or systems with the indoor position tracking system. With linked data sets, more applications can be used based on indoor positioning than just KPI identification. For example, by combining real-time indoor positioning tracking with building information modeling (BIM), users can gain a prompt and direct visual-based awareness of the on-site work situation and thus can flexibly adjust and control the on-site work to improve productivity.

Overall, we have shown that waste is a problem with flows during value-adding activities on-site rather than being caused only by a single worker or by individual materials being misplaced. The use of presence information from both workers and materials can offer simple KPIs that can act as proxies for waste indication—for instance, to evaluate how much the presence of workers and material kits would be affected by JIT logistics (e.g., kitting practice) in different projects.

Limitations

The current research does have a few limitations. One of the main limitations of this method may be described as identification issues of materials and kits. Based on the real-time tracking system used in this case, which showed satisfactory coverage (97.1%) and accuracy (88.4%), we saw relatively good results from worker and material timestamps to reduce resource flows on-site. We were unable to identify the presence of specific materials in the kits, however, because we only placed beacons to monitor the kits in our study. In future studies, we propose to add features such as sending notices to workers for simple confirmation of their current activities (such as waiting for materials, idle status, etc.) when the TMA degree appears to decrease during the day. In this way, sorting through all uninterrupted worker presences to search for time durations could be avoided, which hinders the effectiveness of the kitting solution. We would also be able to learn the actual reasons for better effectiveness from workers' direct confirmations.

Another limitation is that one beacon for the A3 kit was lost onsite, so the NM periods may have included times in which workers were actually with the A3 kit, thus making the actual NM smaller. In this case, some indication of the effectiveness of the underlying kitting practice could still be obtained by examining the value of TMD and checking on a worker's status with the correct material kits in an apartment (i.e., the designated kits). For future study, beacons will be tagged with the material kits all the time during the tracking periods.

In this research, Linked data method was implemented to integrate the heterogeneous indoor positioning and the operation schedule information. Such integration combines data sources from different systems, and further enables the calculation of the KPIs with schedule compliance (STMD and STMA) that cannot be achieved with solo data streams based on previous methods. However, in this research only these two data sources were obtained, which means that only STMD and STMA can be calculated. If more types of data sources could be acquired, more potential KPIs could be also calculated. For example, if the BIM model of the project could also be obtained, it is possible to use the BIM quantity takeoff to calculate the workload of each task in the schedule, and further to calculate the work efficiency of each task. In the future research, the goal is to collect comprehensive digitalized data from one construction project and integrate all digital data sources and develop more accurate KPIs to represent the construction productivity.

CONCLUSION

In this paper, we have illustrated how our proposed real-time tracking system and linked data framework were applied in an indoor bathroom renovation construction project for the automated detection and analysis of time-matching levels of material kits and workers based on their uninterrupted presence. New KPIs were developed that can be measured in real time and offer opportunities to improve material and labor flows for kitting logistics solutions based on the proposed metrics. We have learned that notable durations occurred in work locations in which workers were without kits on-site. The variability of these durations in different places should be noted for managing kitting solution practices.

Compared to tracking for workers only, the information in this work consists of the integration of labor and material tracking and the evaluation of current kitting logistic solutions based on overlapping times of workers and kits. The current method works by revealing the observed problems of kitting practices in real time, thus providing lean intervention opportunities for material-labor-related tasks on-site. Users can also evaluate the effectiveness of the kitting practice in work locations based on the metrics introduced in this paper. We aim to establish a linked data model that could be used to connect heterogeneous information of cross-type resources (such as labor and materials) and their schedules from external sources in construction so that an automated data analysis for proposed KPIs (such as STMD and STMM) could be executed smoothly for site managers' decision-making in the future.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article can be made available by the authors upon request.

AUTHOR CONTRIBUTIONS

Conceptualization, JZ, YZ, OS, and AP; Methodology, JZ and YZ; Data Collection, JZ; Data Analysis, JZ and YZ; Writing—original draft, JZ; Writing—review and editing, JZ, YZ, OS, MT, and AP; Funding acquisition, OS.

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Differences in Experiences With the Development of Mixed-Use Projects From 2004 and 2017

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Mixed-use developments, having three or more uses within one development, have several benefits for communities, however due to the complexity of these developments, several challenges arise in the planning and development phases. The main challenges are local regulations, neighborhood opposition, financing, and insufficient market interest. A 2004 survey of these challenges was repeated in 2017 and the differences between the two are compared in this paper. Significant differences were found in the frequencies of the challenges, mainly that the proportion has dropped in 2017. However, local regulations remained the most significant challenge encountered. The decrease in frequencies is conceivably a sign that regulators, financers, and members of the community are becoming more familiar with mixed-use developments.

Keywords: mixed-use development, regulations, neighborhood opposition, market interest, financing

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INTRODUCTION

Mixed-use development, multiple uses within a project, although not a new concept, is continuing to grow in popularity. Mixed-use development has several benefits for communities and is a key strategy in achieving sustainable environments (Woo and Cho, 2018). It has been utilized as a popular method for community revitalization, helping to increase density which helps grow communities with limited land space or empty city centers and create a vibrant space for people to enjoy. Additionally, the developments provide benefits to the environment, retailers, residents, and municipalities. Increasing the walkability of an area can reduce commuting distance and auto mode share (Lee, 2020) and thus reduces pollution. Offices and retailers within a mixed-use development become immersed in potential customers from the diverse residents and other businesses (Chinburg Properies, n.d; Slowly, 2016). Because amenities are closer to home, mixed-use developments promote walking, which provides health benefits for residents (University of Delaware De). Further, it is estimated that nearly 33% of people would prefer to live in a diverse, walkable community (Slowly, 2016). Municipalities see a tax revenue in-crease from mixed-use versus single use and are able to save on infrastructure construction, such as roads and water supply, because of the shared land use (University of Delaware De; Newcomb, 2015; Lamb, 2012; Useful Community Developm, 2017). Any one of these assets would be a reason to promote mixed-use development, to say nothing of simply overcoming obstacles to its provision. In combination, they form a compelling case for mixed use as an element of a more inclusive and prosperous society.

Levine and Inman used the Urban Land Institute definition of mixed-use developments as having three or more uses in one project (Urban Land Institute, 2011; Levine and Inam, 2004) as this very premise makes mixed-use developments popular, it also creates challenges. Zoning, building codes, and appropriate uses are some of the prominent challenges developers face when planning this type of project. Transferring one development's successful practices to another development rarely result in the same outcomes. For this reason, it has proven difficult to determine best practices for these types of projects.

In 2004, Levine and Inam (2004) from the University of Michigan performed a nation-wide survey of developers to determine the highest impact challenges to mixed-use developments. The present study has recreated the survey to determine if there are significant changes in challenges to the use of mixed-use developments in 2017. Further, the current survey also collected the opinions of planners, architects and construction managers as they are the stakeholders most involved with the upfront planning processes involved for mixed-use development and represent their own aspects, opinions, and goals for the success of the project. This study aims to answer the following questions:

- What are the current factors affecting mixed-use development as perceived by developers, planners, architects, and construction managers?
- What are the differences in the factors of local regulation, market interest, financing, local opposition, in a survey of developers in 2004 (Levine and Inam, 2004) and 2017?

METHODS AND MATERIALS

Literature Review

Mixed use development has become a popular tool to revitalize communities, increase sustainability, and develop a stronger sense of community. The exact definition of mixed-use development is relative from country to country (Lau et al., 2005). In the United States, the Urban Land Institute (Urban Land Institute, 2011) defines mixed-use as "three or more significant revenue-producing uses (that have a) functional and physical integration of project components" (p. 2). AdditionallyLau et al. (2005) suggest that no single-use should utilize more than two-thirds of the usable floor plan of the project. The potential uses for the project include "real estate with retail, office, residential, hotel, recreation, or other functions that are pedestrian-oriented" (Rabianski et al., 2009) (p. 206). These uses encompass the popular live-work-play environment for people where everything needed is comparatively close. However, despite these definitions, one mixed-use development approach and plan rarely results in the same success amongst various projects; this is due to the various ways in which mixing uses may be applied.

According to Grant (2002), there are three main ways that a community may apply mixed-use: increasing the intensity of land uses, increasing the diversity of uses, and integrating segregated uses. Intensity of land use is known as the variety of choices of a specific type of use; multiple types of retail or housing choices to accommodate all levels of income (Niemira, 2007). Projects may be as large as entire neighborhoods, an entire street or block, or as small as an individual building; located in inner city or city centers, brownfield or greenfield sites, or city edges such as suburbs (Rowley, 1996). These projects are typically implemented as an attempt to promote mixed use developments through "1) conservation of established mixed-use settings; 2) gradual revitalize and incremental restructure of existing parts of towns, such as infill development and reuse, conversion and refurbishment; and 3) comprehensive development or redevelopment of larger areas and sites" (Rowley, 1996) (p. 87). **Table 1** summarizes the variables of these factors.

These various factors and their options of mixed-use give more credence to the idea that the same urban form may not be successful in another development; yet can be adaptable as needed, provided the proper planning is performed. This also shows that mixed-use development can occur on several different scales and can intertwine together in various environments; thus, a critical analysis should be performed to determine the best approach to incorporate the proper setting, location, and timing.

As mixed-use developments have evolved, so has their popularity. Rowley (1996) points out that due to the diversity of the urban setting, experiences are different than in suburban or rural settings, such as "people, activities, uses, architecture; the amenities, open spaces and other visual stimuli that cities can offer; and a rich public life" (p. 89). Further, many of these services, including retail and public transit, rely on a higher density in or-der to function (Brewer and Grant, 2015). In a survey from four real-estate associations, the top three reasons cited for the popularity in 2006 were: "the live-work-play environment as a single location is convenient; rising land prices are making more density necessary; and the format is being encouraged by local public agencies" (Niemira, 2007) (p. 54). While there are individual benefits to mixed-use development, there are community-wide benefits as well. Hoppenbrouwer and Louw (2005) report that the most significant advantages of mixed-use development are a reduction in travel needs, followed by increased urban diversity, and vitality.

Mixed-use developments generate economic vitality (MahmoudiFarahani et al., 2018) benefits for businesses. Job creation is a strong sign of vitality and a main goal of mixed-use development is mixing residences and offices to provide easy access to employment and clients (Grant, 2002; Hoppenbrouwer and Louw, 2005; Grant and Perrott, 2011; Kong et al., 2015). Businesses actually prefer to be in mixed-use as some of their client-base is already created just by proximity (Chinburg Properies, n.d; Slowly, 2016); for example when stadiums or arenas are in the community, there are "50,000 people will want to have something to do before and after the game other than hangout in the parking lot" (Slowly, 2016) (para 9). Even on a smaller scale, a community with a theater or playhouse has the same need, employees have a place for lunch, entertainment, and so on (Efficient Gov, 2015). Diverse uses attract more and diverse people, providing an increased potential for the business to be seen rather than with an isolated location (Chinburg Properies, n.d; Slowly, 2016; University of Delaware De). Further, property managers tend to provide better service as they have more clients within a building, resulting in quicker response to issues, preventative maintenance, and lower costs from sharing the building with other inhabitants (Chinburg Properies, n.d;

TABLE 1 | Factors and variables for the application of mixed-use development.

Factors	Variables
Settings	Districts or neighborhoods
	Street or other public spaces
	Building or street blocks
	Individual buildings
Locations	City or town lefts
	Inner-city or Brownland
	Suburban or edge of town locations
	Greenfield locations
Approaches	Conservation of established mixed-use settings
	Gradual revitalization and incremental restructuring of existing parts of towns, including infill development and reuse, conversion and refurbishment
	Comprehensive development or redevelopment or larger areas and sites
Time	Varying schedules and reasons
	Space sharing for activities

Adapted from "Mixed-use Development: Ambiguous concept, simplistic analysis and wishful thinking?" by Rowley 1996, Planning Practice and Research, 11 (1), 85–98 (Rowley, 1996).

Buildings, 2009). If successful, profits for businesses in mixed-use communities can exceed traditional locations by three times, sometimes more (Leonard and Cumbelich, 2014).

Regulations are required for infrastructure maintenance and economic support. Roads, water supply, drainage, etc. are built to a specific capacity and if these capacities are exceeded they can break down faster, require more maintenance, or may not work at all; thus planners are often unable to accommodate all development requests of higher density. Additionally, uses are regulated by zoning in order to not saturate the market, preserve history, or not disturb residents. One jurisdiction may have different objectives and purposes or different views how to reach them in another district. Besides counties, jurisdictions could also be cities. Each jurisdiction has a committee of people from the community that approves regulations, zoning changes, land use, and construction. These planning committees are led by planners who are professionals that are employed by the city or county in order guide the committee that make decisions on these regulations (City planning, 2016).

Planning staffs and commissions do not always support the mixed-use concept. In interviews performed by Grant (2002), the researcher found that planners of smaller communities hesitate to utilize mixed-use as they doubt the benefits. Instead, they believe that existing neighborhoods need support and that people choose the suburbs for, among other benefits, the separation from other uses. Rowley (1996) suggests that some planners make uninformed assumptions about the community's wants and needs. Further, they underestimate the implications of these assumptions. On the other hand, Brewer and Grant (2015) suggest some planners promote density as a way to increase services within the community; however, their execution is lacking. The thought is that increased density leads to lower housing costs and better support of mixed-use; however, actual the actual populations do not meet expectations. Therefore, services do not have the expected support, resulting in the loss of the anticipated benefits associated with mixed-use development.

Another hurdle in successful mixed-use is identifying proper compatibility of uses. This includes compatibility for community and other uses in the area; Rabianski et al. 2009 describes this as creating a synergy in the community. For proper integration and increased vitality, a market analysis for each use is needed to ensure relevant uses, scale, and location (Anders, 2004; Rabianski et al., 2009). Taleai et al. (2007) found that uses and land types can actually "repel" other uses. For example, although highways provide accessibility, they also create noise which can be problematic for residences (Taleai et al., 2007). Similarly, other competing or over-saturated businesses and uses should be avoided, instead uses should be complementary. Rowley (1996) describes other factors that affect people using mixed-use developments such as having accommodations for the disabled and elderly, various levels of income, and convenience of use. In order to maximize infrastructure savings, space should be designed to be used as often as possible, including outside of normal business hours (Rabianski et al., 2009). In a diverse area, individual schedules can vary greatly resulting in varying times of usage needs. Rowley (1996) suggests sharing spaces, especially for uses that may not otherwise be able to afford the space on their own; for example a building room may host an aerobics class in the morning, a book club in the afternoon, and a card club in the evening. This type of space sharing helps to further maximize available uses and amenities for the community.

Although many people prefer mixed-use city life, there are as many others who do not wish to live in the city. And, while people enjoy the conveniences that mixed-use development offer, some are very cautious about what uses should be mixed. For example, uses such as "group homes, day care centers, waste management facilities, high-density housing, halfway houses, or prisons typically encounter resistance from residents. Even parks and playgrounds sometimes met opposition" (Grant, 2002) (p.73). Brewer and Grant (2015) point out that attempts to increase population densities and mix are affected by household dynamics. For instance, families prefer homes with gardens, that allow privacy for peace and quiet, offer some separation, and provide community-focused amenities (Rowley, 1996). For a long time, the American dream included a home in the suburbs with a white picket fence and living among people who are nearly the exact same, which goes against urban mixed-used development. However, even in 1996, Rowley notes that social networks are only partly shaped by the home locality, mostly dependent on personal mobility, "convenience, choice, and price" are the main factors of determining shopping. Technology since then, such as the internet, hand-held devices, and social media, has developed strong social networks that are not even in the same state. At the same time, mobile applications such as Uber rideshares have made it easier to live without a car, making urban living even more accessible. These cultural variables can differ in intensity from area to area, making research even more indispensable for planning. Determining the best use of space to attract the most people is integral to mixed-use development.

In addition to the comprehensive pre-construction planning process and challenges, there are challenges during design phases as well. All construction must comply with local building codes, however with mixed-use development, each use may be subject to a different code which can slow production and add cost. Additionally, each use requires its own support system; for example, it is necessary for a restaurant to have an isolated exhaust system from the rest of the building, and retailers do not want apartment plumbing pipes visible in their space (Koch, 2004). For each use, building codes require different fire suppression methods, and in a mixed-use these can become even more stringent (Rowley, 1996) due to the mixture and higher density. Furthermore, structural safety can become challenging as well. Retail space is more open and expansive than residential or office spaces. Typically retail is on the ground floor for easy access to shoppers, thus the ceiling of this space must be designed to support the above load. As retailers prefer to have minimal columns in or-der to maximize space and have unobstructed views, a support beam must be utilized. This is very expensive as is requires engineered support beams and more material for construction (Koch, 2004).

Although mixed-use development can help to diffuse economic risk across the variation of uses, there are several economic risks which can detract developers from attempting innovative mixed-use projects (Grant, 2002). As Grant and Perrott (2011) point out, construction costs for these projects are higher than single-use construction, however they do not always generate a sales premium (Rowley, 1996; Koch, 2004; Niemira, 2007). Unfortunately, people outside of the construction process do not always understand what adds costs to projects and therefore do not prefer the premium sales price. During an interview, a principal from Elkus/Manfredi Architects, LTD. stated that mixed-use projects can cost as much as 70% more than in an average suburb (Koch, 2004) where most uses are separated by building. Furthermore, a survey byNiemira (2007) revealed that almost 2/3 of respondents agreed that mixed-use projects have a longer construction time than that of separate components. The longer a construction project lasts, the more expensive it becomes as day to day overhead expenses accrue and cannot be re-covered. Furthermore, investors see mixed-use projects as less prosperous than single-use ones that consequently have a lower exchange value (Rowley, 1996).

However, there are variables which, when present, further increase the chance of success, specifically economic success. Financial returns have the capability to be higher in more dense neighborhoods as they provide more opportunities to accept a mixed-use project. However, smaller cities can lack these drivers of change created from high levels of population influx. Thus, in these cities, more research should be performed to determine the proper economic, market, and political conditions to accept a mixed-use development (Brewer and Grant, 2015). Niemira (2007) survey results, suggests that there are three major factors for financial success: "1) having a major draw–employers, an academic institution, an entertainment facility; 2) developing the project as part of a master-planned site; and 3) having an urban location" (pp. 55–56). Being aware of the unique economic environment in which the project will be constructed will only help to increase the chances of making the development more profitable and attract more investors.

Although there is a consensus on various factors that affect success, previous attempts to utilize explicitly defined best practices have regularly not resulted in the same levels of success from project to project. Further adding to the difficulty of administering best practices, it is difficult to quantify them for a specific area until perceived differences are identified (Hoppenbrouwer and Louw, 2005). Rowley (1996) states that mixed-use development "cannot be divorced from cultural priorities and lifestyles" (p. 85). Moore (Koch, 2004) explains that, especially with mixed-use development, implementation depends on culture, context, etc., therefore best practices are not necessarily transferrable. According to Kong et al. (2015), this means that "different urban forms generally lead to different urban performance" (p. 95). Each project should be guided by the community's social make-up and not assumed that it will revitalize the community as it did in another community (Anders, 2004) nor that all residents within the community will benefit from the project (Grant, 2002).

Although significant challenges in planning and completing mixed-use developments exist, there are several instances of successful projects. Taleai et al. (2007) state the im-portance of planning, which includes analyzing the current market and defining any potential problems. Extensively engaging the community as early as possible (Anders, 2004) also helps to determine market conditions and overcome problems more efficiently. Market analysis includes identifying both successful and competing uses (Taleai et al., 2007). Many agree that location is important as mixed-use performs better when there is more traffic (Grant and Perrott, 2011) and public transportation is within walking distance (Niemira, 2007). Timing is also important as there needs to be enough people to support retail, yet enough businesses to attract people; thus phasing based on community needs is vital to success (Grant and Perrott, 2011).

In an interview by Koch (2004), a president and managing partner of a real estate developer in North Carolina said that to draw people towards the development, he reserves the most visible, ground level portion of buildings for most attractive retailers. Similarly, Niemira (2007) survey showed that including a major draw, such as employers, an academic institution, entertainment, etc., is the number one factor in achieving financial success. The second and third results from

TABLE 2 | Challenges encountered to mixed-use development 2004 (Levine and Inam, 2004).

	Frequency	Percent
Local regulations	531	76.6%
Neighborhood opposition	404	58.3%
Financing	239	34.5%
Other	195	28.1%
Insufficient market interest	178	25.6%

Respondents can select more than one challenge. n = *693.*

TABLE 3 | Challenges encountered described as "other" (Levine and Inam, 2004).

	Frequency	Percent
Land availability	47	24.1%
Cost	35	18.0%
Developer interest	22	11.3%
Public understanding and acceptance	20	10.3%
Transportation and infrastructure	12	6.2%
Policy maker understanding and acceptance	10	5.1%
Financial risk	8	1.0%
Unproven nature of projects	2	20%
Miscellaneous	39	—
Total	195	100%

TABLE 4 | Frequency of most significant challenge 2004 (Levine and Inam, 2004).

	Frequency	Percent
Local regulations	289	42.6%
Neighborhood opposition	119	17.5%
Other	107	15.8%
Insufficient market interest	102	15.0%
Financing	62	9.1%
Total	679	100%
Did not answer	14	—
Total	693	—

the same survey were being part of a master plan and being in an urban location, respectively. Niemira (2007) also found that "almost 60% of industry players and observers who participated in the survey felt that having public-sector involvement in a mixed-use project would help to make it more financially viable" (p. 55).

Levine and Inam 2004 Results

In Levine and Inam (2004) mailed 2,000 surveys to members of the Urban Land Institute. Of the 2,000 surveys, 706 were returned completed and 693 were qualified providing a 36.5% response rate.

The next four tables summarize the main results obtained by Levine and Inam (2004), related to the use of mixed-use development in 2004. **Table 2** summarizes the challenges encountered by the respondents in 2004 and respondents were able to select more than one challenge and write in a challenge that was not listed. The next table, **Table 3** summarizes the designation of "Other" written in. Instead of asking to rank all challenges, the 2004 survey asked two separate questions, the first asking to provide the single most significant challenge, the next question asking to provide the second most significant challenge (**Tables 4, 5**). Local regulations was the most significant challenge with the highest frequency, followed by neighborhood opposition, "other", insufficient market interest, and secure financing. Neighborhood opposition was the second most significant challenge with the highest frequency, followed by local regulations, secure financing, in-sufficient market interest, and "other".

TABLE 5 | Frequency of second most significant challenge 2004 (Levine and Inam, 2004).

	Frequency	Percent
Neighborhood opposition	226	34.3%
Local regulations	204	31.0%
Financing	121	18.4%
Insufficient market interest	55	8.4%
Other	52	7.9%
Total	658	100%
Did not answer	35	—
Total	693	—

Methods

This research used a quantitative approach through the use of a survey instrument. The population for this study was United States organizations involved in the preplanning process of mixed-use projects, these include architects, city planners, developers, and construction managers.

The survey instrument developed for this survey is greatly inspired by Levine and Inam (2004) instrument. Demographic questions were added to the current survey:

- Please tell us about the industry function you are involved with.
- A map was added to determine geographic region.
- How many years of experience does your organization have dealing with mixed-use projects?

The main questions that remained the same between the two surveys:

- What, if anything, do you think are significant barriers to the further development of these alternatives?
- Which of the barriers above what is the most significant and second most significant single obstacle to further development of these alternatives.

Questions were then added about the change of the challenge, if its significance had increased, decreased, or remained the same.

The survey questions were included in an online surveying platform (Qualtrics) and distributed to U.S. based organizations. Organizations were asked to send the survey out to their members, including American Institute of Contractors, American Planning Association, Association for the Advancement of Cost Engineering, Next City, United States Green Building Council; the members of the Purdue University School of Construction Management contact list were emailed directly. Additionally, in the invitation email, participants were asked if they could forward the invitation to other stakeholders, there-fore snowball sampling was also used. Additionally, the survey was also publicly posted in LinkedIn via personal profiles.

The research questions to be answered by the survey are:

- What are the current factors affecting mixed-use development as described by developers, planners, architects, and construction managers?
- What are the differences in the factors of local regulation, market interest, financing, local opposition, in a survey of developers in 2004 (Levine and Inam) and 2017?

Responses to the encounters and significance of the challenges were coded either yes or no. If the respondents had encountered the challenge, yes was coded, or no if not. Chi square tests were completed to test the proportional frequencies from the 2004 answers compared to the 2017 answers. However, the ranking of first and second most significant challenge was not tested individually, but as the overall ranking of all challenges.

TABLE 6 | Frequency of role of respondents.

Role	Frequency	Percent
Planner	3	2.8%
Developer	6	5.6%
Construction Manager	64	59.8%
Architect	34	31.8%
Total	107	100%

TABLE 7 | Challenges encountered to mixed-use development.

	Frequency	Percent
Local regulations	54	50.5%
Financing	40	37.4%
Neighborhood opposition	40	37.4%
Other	18	16.8%
Insufficient market interest	14	13.1%

Respondents can select more than one challenge. n = *107.*

RESULTS

Descriptive Statistics

Table 6 shows the distribution of the roles of the 107 respondents. Both Construction Managers (*n* = 64) and Architects (*n* = 34) had a higher response rate than other stakeholders. Unfortunately, the reach to Developers (*n* = 6) and Planners (*n* = 3) was lower than expected. Because it is unknown which organizations actually distributed the email, it is impossible to know the response rate, however, based on responses, it is assumed low.

The initial question regarding challenges to mixed-use development asked for all challenges and barriers encountered, **Table 7** summarizes the responses. For this question, respondents could select more than one answer and write in a response not provided. Local regulations is the most frequently selected challenge with 54 selections, followed by financing and neighborhood opposition, each selected 40 times. Insufficient market interest is the least frequently chosen with only 14 selections. The "other" option was selected 18 times with challenges written by respondents, **Table 8** provides the designation for these selections.

When asked to rank the challenges in **Table 7** from one to five with one being the most significant and five being the least significant, 64 of the respondents participated. The frequency of the ranking of each challenge can be seen in **Table 9**.

Analytical Statistics

It is important to note that not only is there potential for change over time, but between the two populations. In 2004, Levine and Inam (Levine and Inam, 2004) were able to reach developers, however in 2017 the same population was not able to be reached and resulted in mostly construction managers and architects.

The survey asked respondents to rank their first and second most frequent challenge; these responses can be seen in (**Tables 10**, **11**). The survey question asking which challenges were encountered by respondents (**Table 7**) was compared to the similar question from the survey in 2004 (**Table 12**) to answer the second research question "What are the differences in the factors of local regulation, market interest, financing, local opposition, and possibly others to a survey of developers in 2004 and 2017?" **Table 12** summarizes the data. Local regulations remains the most frequently encountered.

TABLE 8 | Challenges encountered described as "other".

—	Frequency	Percent
Construction cannot occur fast enough to keep up with demand and growth	4	22.2%
Financial risk	3	16.6%
Market saturation	2	11.1%
Lack of land/land cost	1	5.5%
Complexity of construction and design	1	5.5%
Lack of implementation knowledge	1	5.5%
Developer interest	1	5.5%
Harder for small firms	1	5.5%
No retail involvement	1	5.5%
Project type not the norm	1	5.5%
Total	18	100%

Respondents can select more than one challenge.

TABLE 9 | Current frequencies of challenges rankings.

—	Insufficient market Interest		Local regulations		Secure financing		Neighborhood opposition	
	Freq	Percent	Freq	Percent	Freq	Percent	Freq	Percent
1 Most Significant	11	17.2%	22	34.4%	14	21.9%	9	14.1%
2—	7	10.9%	21	32.8%	14	21.9%	19	29.7%
3—	15	23.4%	14	21.9%	20	31.3%	15	23.4%
4—	24	37.5%	0	0%	15	23.4%	18	28.1%
5 Least Significant	7	10.9%	7	10.9%	1	1.6%	3	4.7%
Total	64	100%	64	100%	64	100%	64	100%
Mean	3.14	—	2.09	—	2.61	—	2.8	—
SD	1.271	—	1.003	—	1.121	—	1.143	—

TABLE 10 | Current Frequency of most significant Challenge.

—	Frequency	Percent
Local regulations	22	34.4%
Financing	14	21.9%
Insufficient market interest	11	17.2%
Neighborhood opposition	9	14.1%
Other	8	12.4%
Total	64	100%
Did not answer	43	—
Total	107	—

TABLE 11 | Frequency of second most significant Challenge.

—	Frequency	Percent
Local regulations	21	32.8%
Neighborhood opposition	19	29.7%
Financing	14	21.9%
Insufficient market interest	7	11.0%
Other	3	4.6%
Total	64	100%
Did not answer	43	—
Total	107	—

However, results indicate that all challenges except financing were significantly different between 2004 and 2017 results. Interestingly, the four (local regulations, neighborhood opposition, insufficient market and other) are perceived as challenges by less respondents in 2017 than in 2004.

Based on the survey question asking respondents to rank challenges, the first and second most significant challenge rankings were compared to the 2004 survey questions asking for respondents to select the most and second most significant challenge. **Table 13** summarizes the responses of the most significant challenge from 2004 to 2017. Local regulations are the most frequently selected as the most significant challenge. Comparing the overall rankings from each year results in a X2 of 11.212 and a p value of 0.024 suggesting that the ranking of 2004 most significant challenge is significantly different than that of 2017. Again, respondents ranked local regulations the most significant, but less by less people in 2017. More people in 2017 perceived financing and insufficient market interest as the most significant challenge.

Table 14 summarizes the responses of the second most significant challenge from 2004 to 2017. Again, regulations are still the most frequently selected as the second most significant challenge. Comparing the overall rankings from each year results in a X2 of 2.738 and a p value of 0.603 suggesting that the results from 2004 are not significantly different from 2017.

DISCUSSION

Although the intent was to compare the same population over time, due to access by the different researchers, the two time period's populations were different: developers and planners versus construction managers and architects. Depending on the type of project contract, construction managers and architects can become involved in the project at different times. Typically, architects are engaged by developers before construction managers, but not always. Construction managers have been engaged earlier in planning phases resulting in more successful completion of projects (Moore, 2013). These variations in project involvement could potentially affect the challenges that each population encounters. How-ever, it is still important to understand the frequency of these challenges, regardless of population, as they are still experienced around the same type of projects–mixed-use developments.

The initial research question regarding current challenges to mixed-use development asked for all challenges and barriers encountered, which was summarized in **Table 7**.

The four provided challenges (insufficient market interest, local regulations, securing financing, and neighborhood opposition) were primarily selected as expected, however the most interesting findings came from respondent's written

TABLE 12 | Changes of percent of challenges encountered from 2004 to 2017.

–	2004	2017	X^2	*p*
Local regulations	76.6%	50.5%	32.267	0.000
Neighborhood opposition	58.3%e	37.4%	16.415	0.000
Insufficient market interest	25.6%	13.1%	8.069	0.005
Other	28.1%	16.8%	6.076	0.014
Financing	34.5%	37.4%	0.342	0.559

TABLE 13 | Changes of percent of most significant challenges encountered from 2004 to 2017.

–	2004	2017
Local regulations	42.6%	34.4%
Financing	9.1%	21.9%
Insufficient market interest	15.0%	17.2%
Neighborhood opposition	17.5%	14.1%
Other	15.8%	12.4%
Total	100%	100%

2004 n *= 693 (14 did not answer). 2017* n *= 107 (43 did not answer).*

TABLE 14 | Changes of percent of second most significant challenges encountered from 2004 to 2017.

–	2004	2017
Local regulations	31.0%	32.8%
Neighborhood opposition	34.3%	29.7%
Financing	18.4%	21.9%
Insufficient market interest	8.4%	11.0%
Other	7.9%	4.6%
Total	100%	100%

2004 n *= 693 (35 did not answer). 2017* n *= 107 (43 did not answer).*

submission for the "other" se-lection. While there are several challenges written in, three new challenges were discovered compared to the 2004 survey:

- keep up with demand and growth
- lack of implementation knowledge and development modeling
- these projects are becoming harder for smaller firms

Other challenges were also written in, but are expected from the literature review and 2004 survey; included financial risk is too high, market saturation, complexity of construction and design, no retail involvement, lack of land and land costs, insufficient developer interest, and these projects are not the norm in their NW market.

Local regulations is ranked the most significant and second most significant challenge. In order after regulations, the ranking of the most significant challenge are financing, in-sufficient market interest, neighborhood opposition, and the other category. In order after regulations, the ranking of the second most significant challenges are neighborhood op-position, financing, insufficient market interest, and the other category.

Difference From 2004 and 2017

In analyzing the differences from 2004 to 2017, the percent of the frequencies encountered for each of the years were compared, these are summarized in **Table 12**. As mentioned above, there are three new challenges not mentioned in 2004. All of the challenges saw a significant decrease ($p \leq 0.05$) in the proportion of people who encountered these as challenges, except for the financing challenge. This may be for a few reasons: regulators and people in the local community are becoming more familiar with mixed-use developments. Regulators are understanding how to better accommodate these types of construction and are better prepared to handle them. The local community has changed their wants and enjoy the ease and convenience of a live-work-play environment. However, the other explanation for the significant change in encounters is simply the populations that were reached. The 2017 population was compromised of mainly general contractors and architects who may not be as involved in the early planning stages of mixed-use development and therefore may not encounter as many challenges.

When looking at the ranking of the challenges, both in 2004 and 2017 each year the first and second most significant rankings slightly change, **Table 13** and **14** shows the differ-ences in percentage of ranking. However, only the most significant ranking saw a significant change with the overall *p* value under 0.05.

The analysis of the data from this research has provided several interesting results. First, the new challenges identified through the "other" designation provides insight into the current market within the last few years. Not being able to keep up with demand for construction can occur from a few possibilities. Lack of labor force is reasonably the most significant cause, both in manual and office labor. (Baiden et al., 2006). The average labor participation rate in the United States for January through June of 2017 is 62.8%, a 5.4% decrease in the past 10 years, part of an ongoing trend of the past several decades. However, the construction industry perhaps has been hit the hardest; according to several news organizations such as Forbes (Beyer, 2017), Fox Business (Grant, 2017), CNBC (Olick, 2017), Slate (Gross, 2017), and the like have reported on the ongoing shortage of construction labor. This shortage has continued to decline, especially in the last year (Valenti, 2021).

The difficulty of securing financing can also cause issue with supplying demand as does limited land availability. Requesting a development model solidifies one of the main is-sues with mixed-use development in that project planning best practices, unfortunately, do not always work with these projects (City planning, 2016). Constructing an exact replica of a successful project in a different area can result in a drastically different outcome. The community and economic wants and needs must be identified in order to plan for the most successful uses within the development. The last new challenge identified was that it is harder for smaller firms to participate in these types of projects, which can be explained by the other new challenges. A smaller firm cannot always compete with larger firms (Valenti, 2021). High hourly wages and complete benefits can be more arduous for a smaller firm to offer, especially in comparison to larger firms. Further, financing, insurance, and bonds for construction is based on firm experience and size, thus it is more difficult for a smaller firm to actively complete with a larger firm on these projects. While it may be easy for a small firm to complete a single use project, the combination and size of a mixed-use development can make it too difficult for these firms.

Local regulations have remained the most significant challenge, but its frequency has significantly decreased. Neighborhood opposition has also changed since 2004, decreasing in ranking as a challenge. The old fashion idea of the "American Dream" has changed from a suburban house with a white picket fence (Govindarajan et al., 2016). This change could be driven by younger generations who either do not want or cannot afford their own transportation, more sustainable communities, be more mobile (not owning a house), have less maintenance association with a suburban home, and/or wish to support smaller, more local businesses. The appeal of a "live-work-play" community also attracts older generations whose children are now out of the house and may have the same wants that younger people have, as listed above. Also, those whose health may prevent them being able to drive and wish to avoid isolation are also attracted to mixed-use neighborhoods where amenities are more easily accessible. A 2020 survey by the National Association of Realtors (National Association of Realtors, 2020) shows that all age groups, including older generations, show more interest in walkability near their home and less focused on access to highways. However, the survey does show that 60% of people surveyed want a larger yard with more outdoor space and less people around (National Association of Realtors, 2020).

Recommendations

While this research identified new and changes of significance in challenges, there is further data that should be collected. First, more planners and developers need to be reached to survey so that there is sufficient data in order to statistically determine any differences in the view and experience of challenges. Further, interviews should be completed in order to better understand these challenges and what has been done to overcome them, specifically related to local regulations and securing financing as these are the top two most significant challenges.

More data is also needed to discover why demand cannot be met, if this is actually an emerging challenge that is widespread, and if this is an issue specifically related to mixed-use developments or all construction projects in general. The cause of this challenge, whether it is being able to secure financing, having proposals rejected, lack of labor force, or something completely different, will drastically affect the way in which it is over-come.

Local regulations have been an ongoing issue for mixed-use development. Two main actions should occur to help combat this issue: policy change and education. All roles should be provided more resources in order to better understand mixed-use development, their benefits, and how they can help streamline the implementation process, particularly where mixed-use is a new concept to a community. Educating each role of all perspectives and challenges is important for any interdisciplinary team, especially in this these types of projects. When all parties can understand each other better, issues can be more easily and quickly solved. With education, policy change should be encouraged as well. As presented in the literature review, other countrie's zoning are much more mixed-use friendly, have less strict definitions of zoning/classes to allow for mixed-use without amendments or need for rezoning approval and there are often public/private partner-ships to aid in starting and completing a project. This type of partnership aids in the is-sue of securing financing for a project. Financial regulations have caused the approval process for all types of loans to be more difficult. Changes in financial regulations are more difficult to achieve, but public/private partnerships can help to alleviate some of the financial strain for these projects. Providing more educational information will also help banks make more educated decisions on lending and overall polices. However, before being able to provide a rich context-based resource to those participating in mixed-use development, more research must be completed, as described above.

Further, research should be conducted on the interconnectedness of the challenges. For example, the inability to secure financing, delays due to regulations, and lack of labor force may contribute to not being able to meet demand. Neighborhood opposition may affect the opinion of the city planners and how they enforce the local regulations. Local regulations may impact the availability to secure financing through a bank. Other relationships may exist such as these that are unknown. Understanding these connections will further lend itself to the understanding of the cause and more importantly, the solution of these challenges.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Purdue University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JM researched and wrote the entire paper.

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Defining Supply Chain Visibility for Industrial Construction Projects

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Good Supply Chain Visibility (SCV) is vital for on-time delivery and installation of materials on industrial construction projects. SCV is possible via the exchange of information about materials in the supply chain. Prior academic research has highlighted the importance of SCV. However, the literature lacks the detailed definition of visibility that can be easily applied to projects. This research reviewed prior studies on SCV and adopted an appropriate definition that supports relevant decision-making on industrial construction projects. From this definition, the research objective is to develop detailed operational definitions of information needed to support supply chain decisions on industrial construction projects. The study employed mixed methods that consisted of interviews, review of mini-cases of industrial projects, procurement and material tracking tool assessment, and group discussions in structured workshops with a panel of subject matter experts. The research developed 79 detailed information needs and associated definitions that support ten key supply chain decision areas across detailed design, procurement, and construction phases of industrial construction projects. These definitions were evaluated by multiple means including an external team and a case study of an industrial construction project. The definitions developed by this research will enable both researchers and practitioners to invest in better measurements of visibility and support development of new tools and techniques.

Keywords: supply chain visibility1, information sharing2, construction supply chain3, industrialized construction4, supply chain decision-making5

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1 INTRODUCTION

Supply chain visibility (SCV) refers to making informed decisions using the timely and accurate exchange of information between the participants as the materials move in the supply chain (Francis, 2008; Goh et al., 2009). Good SCV is found to improve coordination of material movement (Closs et al., 1997), increase agility and responsiveness of the supply chain (Patterson et al., 2004), reduce distorted information exchange (Dejonckheere et al., 2004), better inventory management (Huang and Gangopadhyay, 2004), and reduce costs (Huang et al., 2003). SCV is a common term and significantly researched concept in the broader supply chain domain (Caridi et al., 2014). Studies in general manufacturing, supply chain, and logistics community have documented topics such as defining SCV (Tohamy 2003; Francis 2008), measuring SCV (Caridi et al., 2010), quantifying benefits of improved SCV (Barratt and Oke, 2007; Caridi et al., 2014), and investigating operational activities in the supply chain that need visibility (Barratt and Oliveira 2001; Prater et al., 2005) to name a few.

The SCV of materials in industrial construction projects is reported to be low (Dharmapalan and O'Brien, 2018). These projects involve multiple supply chain participants who participate in varying capacities during the project's different phases (Caldas and Gupta, 2017). The materials required for such projects are often sourced world-wide and traverse through various supply chain locations before reaching the final installation point at the construction site. During this journey, materials go through a lifecycle of their own. They are designed, procured, fabricated, stored, loaded, transported, unloaded, consolidated, inspected, inventoried, packaged, and installed (Hunter, 2014). Supporting this physical flow, a large amount of information gets generated during the material's lifecycle (Lee et al., 2013). However, the supply chain participants only have easy access to the information within their organizational boundaries (Swaine et al., 2014). They need to exchange this information accurately and on-time with the other relevant participants to support decision-making in the supply chain. However, the exchange of information between supply chain participants is limited (Young et al., 2011). Even if there is an exchange of information, it is not always accurate, complete, on-time, and sufficient (Zhong et al., 2017). As a result, information sharing is ineffective, which, in turn, negatively impacts the decision-making process of stakeholders, leading to costly expediting, ineffective inventory management, out-of-sequence work, quality deficiencies, reduced productivity and safety (Kaming et al., 1998; Caldas et al., 2014).

To improve information exchange in the supply chain, the practitioner-oriented and academic literature in construction, so far, have examined and invested in Information Technology (IT) solutions that enable a digital exchange of information between supply chain participants (Young et al., 2011; Aram et al., 2013). Researchers have also examined the information flows of materials in the supply chain (Ergen and Akinci, 2008; Akcay et al., 2017) as well as used process mapping and modeling tools to visually depict material and information flow data (Arbulu and Tommelein, 2002; Akel et al., 2004; Fontanini and Picchi, 2004). While these efforts establish the need for visibility through information sharing, a detailed assessment of SCV is missing in the construction body of knowledge. This paper is part of a study that attempts to bridge this knowledge gap for capital projects in the industrial sector. The recent article by Dharmapalan et al. (2021) assessed the differences in viewpoints between owners, contractors, designers, and suppliers regarding the status of visibility at major supply chain locations and for common material types of industrial construction projects. The examination was based on data collected using a large-scale survey administered in North America and analysis of the survey data by the four stakeholder types. The current paper focuses on defining supply chain visibility (SCV) in detail for the industrial construction projects. There is limited understanding of how information exchange enables visibility. Specifically, the information is not well defined and fails to account for the supply chain participants' specific needs. Furthermore, there is limited knowledge about the supply chain's key decisions and what detailed information about materials is adequate to support the key decisions.

This study identified the key decision areas during detailed design, procurement, and construction phases of industrial construction projects. It also identified the information needs that support the key decision areas. Finally, the study developed detailed definitions of the identified information needs. To achieve these objectives, the study employed mixed methods that consisted of interviews, review of mini-cases of industrial projects, procurement and material tracking tool assessment, and group discussions in structured workshops with a panel of subject matter experts. The remaining sections of the paper are organized as follows. The literature review and research objectives are discussed in the following section. Next, the methodology section provides details on how the research was conducted. The results of the study and evaluation of the research findings are discussed in the results section. Finally, conclusions are drawn in the last section, including contributions and directions for future work.

2 LITERATURE REVIEW

Literature review involved understanding how supply chain visibility is defined in the broader business literature, followed by a review of information sharing and decision-making related research in the construction industry. The goal and research objectives which this research aims to fulfill is then presented.

2.1 Supply Chain Visibility Definitions

SCV originated in the general supply chain management and logistics domain, and it has multi-disciplinary roots in literature. So, the theoretical basis and supporting research on the concept are broad (Fawcett et al., 2007). A large body of research has focused on defining SCV. **Table 1** provides a list of definitions of SCV.

Visibility is closely related to information sharing. Therefore, some researchers use both the terms interchangeably (Swaminathan and Tayur, 2003), implying that visibility is achieved through access and sharing of information. For example, Swaminathan and Tayur (2003) define visibility from an information availability and sharing viewpoint. Others, such as Bradley (2002), view visibility as a concept discussing software and IT solutions that enable information sharing within the supply chain. At the same time, some authors (Gustin et al., 1995; Closs et al., 1997) have argued that information availability and sharing is not sufficient for SCV and that it is essential to have accuracy, trustworthiness, timeliness, and relevance of the exchanged information. Barratt and Oke (2007) view visibility from a resource-based strategy; they contend that information sharing is the activity and that visibility is the capability that is the outcome of the activity. They further pointed out that visibility is viable through technology and non-technology enabled deployment of resources. McCrea (2005) moved beyond the simple information perspective and proposed a definition that views information as a triggering event, which leads to action. Goswami et al. (2013) define SCV from a decision-making perspective by linking information with decision-making purposes. Similarly, Tohamy (2003) and Goh et al. (2009) contend that availability and sharing of quality information (accuracy, trustworthiness, timeliness, usefulness) do not offer

TABLE 1 | SCV definitions.

Author	Definition
Bradley (2002)	"Direct insight into the status of orders, inventory, and shipments across the supply chain"
Swaminathan and Tayur (2003)	"Ability to access/share information across the supply chain"
Barratt and Oke (2007)	"The extent to which actors within a supply chain have access to or share the information which they consider as crucial or useful to their operations and which they consider will be of mutual benefit"
McCrea (2005)	"The ability to be alerted to exceptions in supply chain execution and to enable action based on this information"
Goswami et al. (2013)	"Having access to relevant information that can be used for various supply chain related decision making"
Tohamy (2003)	"Capturing and analyzing supply chain data that informs decision making, mitigates risk, and improves processes"
Goh et al. (2009)	"The capability of a supply chain player to have access to or to provide the required timely information/knowledge about the entities involved in the supply chain from/to relevant supply chain partners for better decision support"

SCV automatically and that decision-making aspect needs to be considered.

The authors agree with the conceptualization of visibility by Barratt and Oke (2007), Tohamy (2003), Goswami et al. (2013), and Goh et al. (2009), and defined visibility for this study after them. Thus, visibility is the result of accurate, timely, and relevant information exchange about the state of materials between the stakeholders in the supply chain that enables decision making, risk mitigation, and process improvement. The authors adopted this definition since it is the union of crucial elements of the definitions by Barratt and Oke (2007), Tohamy (2003), Goswami et al. (2013), and Goh et al. (2009), and it captures the measurable attributes of visibility. While this definition states the need to have information that supports decisions, it cannot be readily applied to construction projects since it lacks the details about the information needs and the supported supply chain decisions. These two aspects of the construction industry are reviewed next.

2.2 Information Sharing in Construction

A stream of research has been performed to examine the information about materials that need to be exchanged and tools to aid information transfer. An example of information research is the work of Akcay et al. (2017). These authors documented the information flow of structural steel components in the supply chain to highlight the importance of information exchange and understand the steel supply chain's "design, fabrication, shipment, and erection" processes. The information generated and utilized the steel components' features including geometry, material characteristics, connections, and molding information (Akcay et al., 2017). Similarly, Ergen and Akinci (2008) identified and grouped the primary information flows for precast components that need to be shared in the supply chain. The leading information groups include "design information, material information, component quality control reports, and coordination information."

The area of research on tools has used IT to automate the transaction process of materials and facilitate the sharing of information about materials digitally between supply chain participants. For example, authors have used Radio Frequency Identification (RFID) (Song et al., 2006), integrated Global Positioning System (GPS) and handheld computers (Caldas et al., 2006), and also combined RFID and GPS (Torrent and Caldas, 2009) to improve visibility of engineered materials in the laydown yard of industrial construction sites. Similar technology combinations have also been used to improve the visibility of prefabricated materials in the storage sites at offsite fabrication yards (Ergen and Akinci, 2008). The information that is exchanged in electronic format includes information about "shipments, packing lists, inspections, purchase orders, fabrication progress, material receipts, material storage and location, material withdrawal requests, material pick and issue lists" (Dharmapalan and O'Brien, 2018).

While the current research highlights information flows and tools to facilitate their efficient transfer, the information items in these studies are not in detail, limited to specific problems within functions (procurement, material tracking, quality control), or capture data at specific locations in the supply chain and of certain material type. Also, the data provided by these studies is not flexible to the needs of the participants in the supply chain and fails to account for the dynamic nature of the construction industry (O'Brien et al., 2004), thereby causing inefficiency in the decision-making process. The importance of this decision-making aspect in the supply chain is discussed next.

2.3 Decision-Making in the Supply Chain

Decisions support an effective supply chain management of the flow of information, material, and funds. Previous research in construction (Arbulu and Tommelein, 2002; Elfving et al., 2002; Azambuja and Formoso, 2003; Polat and Ballard, 2003) have used models to visually depict supply chain configurations and provide insights for supporting decisions in the supply chain. As an instance, Arbulu and Tommelein (2002) applied Value Stream Mapping (VSM), a tool developed to represent flows of information and material, to support the evaluation of different supply chain configurations for engineered materials. Akel et al. (2004) and Fontanini and Picchi (2004) used VSM models and presented data about processes, material, and information on a more detailed level. While the authors of these studies contend that their results provide support for strategic, tactical, and operation level supply chain decisions, there is, however, no explicit mention of the decisions or decision areas.

Another body of research in construction focuses on decisions or a subset of decisions in the supply chain. Among such studies, Azambuja and O'Brien (2009) identified supply chain decisions that spanned across detailed design, procurement, and construction phases of a construction project. The detailed design consists of decisions regarding the configuration of the

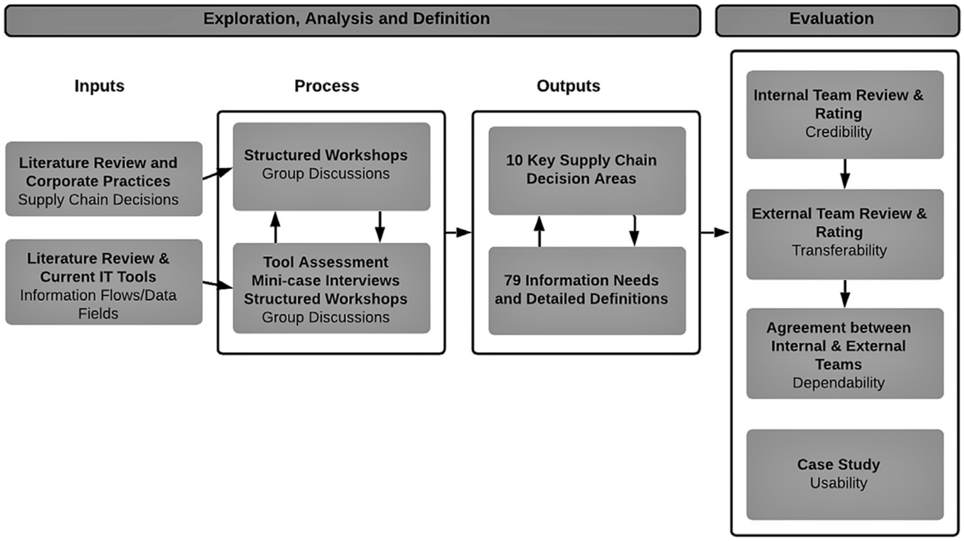

FIGURE 1 | Research process.

supply chain, systems' specifications, and decision regarding constructability. The procurement phase focuses on supplier selection and procurement decisions of materials. The construction phase involves decisions made to protect operations on the construction site from uncertainties in offsite production. In another study, Le et al. (2018) used the decisions by Azambuja and O'Brien (2009) as a basis and examined the decision-making aspect of the construction supply chain. The authors found that the extant literature focuses on twelve decision areas: "supply chain configuration, supplier selection, building partnerships, supply chain management tools, and methods, information systems, risk identification, production planning, purchasing materials, identifying transportation system, site layout planning, material handling, and controlling information flow." While these studies provide supply chain decisions, they are at a high level, skewed towards strategic decisions, and do not mention the information supporting the decisions.

In summary, the review of visibility definitions revealed that SCV encompasses a broader scope and depends on the efficient exchange of information between participants that enables actionable decisions. The extant literature in construction establishes the need for visibility; however, a detailed definition of visibility for advancement is unclear. Specifically, they do not provide information that presents the overall picture on various elements of the supply chain and have not considered supply chain participants' perspectives, which is useful for efficient decision-making. Furthermore, the decisions or decision areas supported by using the information provided by the tools and models are not well consolidated in literature. In other words, there is a need for systematic examination of the detailed information needs about materials and to link them to important decision areas in the supply chain to develop operational definitions of visibility. This study aims to achieve this goal by addressing the following objectives:

- Identify key supply chain decision areas for construction projects in the industrial sector
- Document, define and evaluate the detailed information needed to support the key supply chain decision areas

3 METHODOLOGY

The research process for the study is illustrated in **Figure 1**. The study used multiple research methods to accomplish the research objectives. A mixed approach was used since there were multiple research objectives and due to the dearth of studies in literature that has developed detailed operational definitions of visibility. The research process included two phases: 1) exploration, analysis, and definition; and 2) evaluation. This section describes each phase and the methods used within them in detail.

3.1 Exploration, Analysis, and Definition

The goal of this phase was two-fold: to identify the supply chain decision areas and; to document and define detailed information needs that support the identified decision areas. The identification of decision areas started with a review of literature and corporate practices. For the documentation of information needs, the authors used literature on information, data in current IT tools, and contextual mini-cases as the starting point. Next, the collected data for decision areas and the information needs were processed using structured workshops using a panel of subject matter experts. This sub-section provides details of the structured workshops and the assessment of current IT tools and mini-case investigation using the structured workshops.

3.1.1 Structured Workshops Using Expert Panel

Structured workshop is a useful method when the research involves multiple data collection strategies and the collected

TABLE 2 | Expert panel background information.

Category	Sub-category	Value
Characteristics	Industry participants	18
	Academic participants	4
Years of construction industry experience	Total	320
	Average	14.9
	Minimum	5
	Maximum	30
Organizations represented	Owner	4
	Contractor	9
	Supplier	3
	Designer	2
Primary responsibilities or time spent (%)	Engineering (FEED, Detailed design)	23.8
	Supply Chain (Fabrication, Procurement)	43.7
	Construction	28.7
	Operations (Commissioning, Start-up)	3.8
Industry sector represented	Power-nuclear/non-nuclear	5
	Downstream and chemicals	5
	Upstream, midstream & mining	5
	Manufacturing	3

data needs to be expanded on using discussion between industry practitioners and academic researchers (Gibson and Whittington, 2010). Four academics comprising the authors facilitated these workshops with a panel of industry practitioners, who have experience in the industrial construction sector.

The industry practitioner's panel was chosen since lack of visibility in the supply chain is a practical problem. Additionally, the development of operational definitions of the information needed items required the viewpoints of industry participants. The panel included eighteen industry practitioners from four stakeholder types: four owners, nine contractors, two designers, and three suppliers. **Table 2** provides the detailed background information of the subject matter experts. They had a total of 320 years of experience in industrial construction (mean = 14.9 years) and had worked on a variety of projects including power, downstream and chemicals, upstream, midstream and mining, and manufacturing. Also, the panel had spent 23.8% of the time in engineering, 43.7% of the time in supply chain, 28.7% of the time in construction, and 3.8% of the time in operations phase of industrial construction projects. The multiple stakeholder types and industrial project experience (overall and by phases) was important to the development of unbiased SCV definitions and to focus the research scope on projects belonging to the industrial construction sector. In addition to industry insight, the industry practitioners also assisted with data collection and were the source of industry practices and mini-cases that were used for the study.

The authors conducted the structured workshops using the protocol provided by Gibson and Whittington (2010). For this study, nine workshops were held over 1 year. Each workshop were 1.5 days long; the duration of first day was 8 hours while for the second day was 4 hours. The academic team divided the objectives of this study into smaller tasks that could be accomplished in each of the nine workshops. Before the start of the workshop, the academics shared a pre-read document with the industry expert panel. The document consisted of the workshop's agenda, details about the task or problem to be accomplished, and the resources required to understand and solve the task. These resources were inputs either from literature or from the industry panel or both (see **Figure 1**). Finally, during the workshop, these inputs were reviewed and discussed among the expert panel members. To encourage a thorough and unrestricted discussion, a no-objection rule was established early on and every panel member was provided an opportunity to give inputs. The discussions continued until majority or all of the team members reached consensus and the research objectives were accomplished. During the deliberations, the academic team took notes to record the minutes which were shared with the expert panel for verification. The process of using the workshop for processing information of tool assessment and mini-case investigation is explained next.

3.1.1.1 Tool Assessment and Mini-Case Investigations

The tool assessment aimed to review contractors' information tools (available commercially or developed in-house) to track materials in the supply chain and on the construction site. A structured questionnaire was used for the assessment. It consisted of questions that inquired about the tool's integration capabilities, application area (engineering, procurement, construction), and the data exchanged using the tool.

On the other hand, the mini-cases were based on actual on-going or past projects in industrial construction from the expert panel's organizations. The case selection depended on the representativeness and specificity of the case, which are good attributes to uncover more information and gather insights (Yin, 2009). In this study, the mini-cases had conditions of information needs to support decision making in the supply chain of industrial construction projects. For each mini-case investigation, the academic team conducted one-on-one interviews with the industry expert and the personnel involved in the subject project. Multiple participants within the same project were interviewed. This helped in data's source triangulation and with the internal validity of the findings (Lincoln and Guba, 1985). A structured interview guide assisted in collecting data for the mini-case investigations. The questions of the guide focused on the following: understanding the project and the context that led to the supply chain decision(s), the information visibility that was available and that the project wished to have to support the decision(s), opportunities that were realized or missed as a result of the visibility (or lack thereof), the frequency and severity of the situation, and recommendation or lessons learned. The academic team took extensive notes and generated detailed case-study writeups. The academic team also collected additional supporting data about the case studies for review. These evidence sources included meeting minutes, procurement plan, expediting reports, material delivery reports, and project execution plans. Multiple sources of evidence helped in establishing data triangulation (Eisenhardt, 1989).

The analysis involved the examination of the individual mini-case writeups. First, these writeups were shared with the interviewees. This verification of the writeups by the interviewees supported in achieving construct validity (Yin, 2009). Next, the academic team used inductive reasoning to analyze the cases. Inductive reasoning is part of the theory-building process. It is used to generalize findings of a phenomenon under investigation with the help of specific instances (De Vaus, 2001). Using the mini-cases' specific observations, the academic team generated an initial list of information needs that supported the decisions. The academics then presented the case reports and results to the expert panel during structured workshops. Throughout several workshops, the entire team further reviewed, refined, and finalized the list of information needs to support the decisions and develop detailed definitions for each of the identified information items.

3.2 Evaluation

This phase involved evaluation of the key supply chain decision areas, associated information needs, and definitions. The study used four ways to evaluate the research findings: internally by the expert panel, using an external team, assessing the level of agreement between the expert panel and external team, and using a case study.

3.2.1 Expert Panel and External Team

The evaluation by experts was conducted to establish credibility, transferability, and dependability (Lincoln and Guba, 1985). First, the research findings were evaluated by the internal expert panel. Using structured workshops, the researchers discussed the decision points and information needed items using prolonged engagement, triangulation (sources, methods, and investigators), and member checks (Lincoln and Guba, 1985). The evaluation by the internal expert panel improved credibility of the results. The collective review and feedback also augmented the authenticity of the research findings (Cresswell, 1998).

Next, the authors used an external team to evaluate the content and usability of the research findings. This was particularly important to check for transferability of the SCV definitions to other projects within the industrial construction sector. The external team included four owner, two contractor, and one supplier organization. Multiple participants within each organization participated in the evaluation. They had a total of 194 years of experience in the industrial construction (mean = 27.1 years) and expertise in various industrial sector projects, including petrochemical, pharmaceutical, power, and manufacturing. Also, the distribution of their area of experience included engineering, procurement/supply chain, and construction phases of projects. The evaluation process involved the individual team participant check the decisions, information needed items, and the definitions for their comprehensiveness, quality, and confirmability (Lincoln and Guba, 1985).

3.2.2 Agreement Between Expert Panel and External Team

After the independent evaluation by the internal expert panel and external team, the authors evaluated the degree of consensus between the two groups. This assessment involved checking if there is an agreement among the two groups about the rankings of information needs and definitions. This process helped in evaluating the consistency of the research findings and to check if the findings are dependable (Lincoln and Guba, 1985). The agreement between rankings was checked using Kendall's Coefficient of Concordance (Kendall's W) (Schaeffer and Levitt, 1956). Kendall's W is a non-parametric test used when the data set is small and has many tied ranks (Field, 2009). The authors had both groups rate each information's importance level to rank the information needs using a 4-point Likert scale (1 = Low, 2 = Medium, 3 = High, 4 = Critical). Next, each information-needed item's weighted mean score was calculated using the response numbers in each category (low, medium, high, critical) and the weights (1,2,3,4) of the category. The information needs were then ranked by importance using the weighted mean scores and analyzed for agreement between the two groups using Kendall's W.

3.2.3 Case Study

The purpose of case study evaluation was to check the usability of the research findings (Lincoln and Guba, 1985). A single case was investigated since deductive reasoning was required to show that the set of information needed items is consistent with the investigated case project's information needs. Deductive reasoning is a theory-testing process and can be achieved using a single representative case study (Yin, 2009). It is used to check if the generalization or established theory can be applied to a specific instance (De Vaus, 2001). The investigated project was selected since it had an international supply chain and complex decision-making that needed visibility of materials across multiple locations and stakeholders. Also, the case encompassed multiple decision areas and several information items, thus meeting many requirements of the theory being tested (De Vaus, 2001). According to Yin (2009), such a case can provide moderate convincing test of research finding.

4 RESULTS

4.1 Visibility Needed in the Construction Supply Chain

4.1.1 Key Supply Chain Decision Areas

This study's first objective was to identify the key supply chain decision areas for construction projects in the industrial sector.

TABLE 3 | Project phases and key supply chain decision areas within each phase.

Phases	Key supply chain decision areas	Definition	KSCDA
Detailed Design	Detailing the construction sequence to get materials on site	The ability to accelerate/decelerate the path of construction to ensure the right materials are onsite at the required time	D1
	Reviewing long lead items and need dates	This determines if the engineering sequence of critical components/long lead items is compatible with the schedule	D2
	Identify materials/equipment requiring higher visibility	The critical components/long lead items that need additional visibility based on the nature of the material, confidence in delivery, and critical path	D3
	Establish supplier quality surveillance program and plan	Supplier progress, quality assurance, and control, schedule and performance	D4
	Use of catalog vs. custom	The decision regarding standardized and customized materials to be used and associated planning	D5
Procurement	Order long lead time products	Ordering decision of critical materials that are long-lead items; the time to design and fabricate is the longest	P1
	Supplier selection	The selection of suppliers considering their location, organizational design, handover, and interface management required	P2
	Expediting decisions considering overall project picture	The acceleration, recovery, re-sequencing by monitoring materials/equipment requiring high visibility	P3
	Order commodities/bulk	Ordering decision of non-critical items that have a relatively shorter supply chain period since they have a shorter lead time compared to critical items	P4
Construction	Adjustment in schedule and supply chain to accommodate materials flow disruption	The decision during scope/design change that requires acceleration/deceleration/re-sequencing/recovery; starts with constraint management (reviewing lookaheads), followed by expediting and recovery if constraints not met	C1

The academic team provided a preliminary list of supply chain decisions identified by Azambuja and O'Brien (2009). The detailed design phase includes "defining products/technologies, constructability, modularization, prefabrication, evaluating supply chain configurations, and identifying risks." During the procurement phase, the decisions include the "order of long lead time products, make or buy products, selection of subcontractors and suppliers, geographical locations of suppliers, risk allocation via contracts, risk mitigation via capacity buffers using suppliers, and fixing of supply chain configuration." The construction phase involves "risk mitigation decisions via inventory and time buffers, inventory and time buffer sizes, locating inventory buffers, and risk mitigation via capacity buffers using subcontractors." These decisions provided a reasonable basis for the identification of key decision areas. Also, the industry panel members contributed examples of supply chain decisions that their respective organizations make during a project's lifecycle. In the end, the process led to the identification of more than fifty supply chain decisions across the following phases: initial conception, basic design, detailed design, procurement, and construction.

Next, the team reduced and finalized the decisions during one of the structured workshops. The process involved several rounds of review and refinement (add, deduct, modify) until the team members collectively arrived at a consensus on the list of decisions. During the review, the team members systematically checked each decision for logic and relevance. To aid the process, the team focused on the most important decisions and limited the scope to tactical and operational decisions that needed to be taken during execution once the supply chain was configured. This process reduced the decisions to thirty across the detailed design, procurement, and construction phases.

Furthermore, the team identified that some of the decisions were milestones (define products), processes (construction schedule logic), information (design information) within decisions. This led to combining many decisions and further reduced the list of decisions into ten key decision areas. **Table 3** presents the final list of key supply chain decision areas (KSCDA) and their respective codes, organized by phase from detailed design through construction. These ten decision areas represent a complete set since they are the important ones consolidated from thirty decisions across detailed design, procurement, and construction and focus on tactical and operational level decisions during project execution. The detailed information needs that support these decision areas and their definitions are presented next.

4.1.2 Information Needs and Definitions

The second objective required developing and defining the detailed information needs that support the ten key decision areas. The team used findings from the literature, tool assessment, and mini-case studies to achieve this objective. First, the academic team shared and presented relevant studies in construction that examined information about materials generated or tracked in the supply chain. The studies by Ergen and Akinci (2008), Akcay et al. (2017), Song et al. (2004), Song et al. (2006b) were used as a starting point and facilitated the initial deliberations among panel members.

Next, the assessment of tools of industry practitioners provided information in their in-house procurement and material tracking tools. The authors interviewed five software vendors and seven contractor organizations. As part of the assessment, the participants also demonstrated their respective tools, contributed screenshots and relevant documents. This exercise informed the data fields about materials currently tracked as the material moves in the supply chain.

The results of the tool assessment revealed the following. First, there is a lack of standardization among the tools and inconsistency in material data tracked by companies over the

TABLE 4 | Summary of case studies supporting information needed for key supply chain decisions.

KSCDA	Case number	Project context	Problem	Information visibility needed
D3, P1, P4	CS1	Mid-life refurbishment of large power generation facility—replacement of feeder pipes, fittings, and tubes	Material shortages, late deliveries, quality issues affecting the critical path. Tracking procurement and deliveries were challenging since numerous contractors were working on the project	Information about materials on the critical path; procurement and delivery information of materials by the individual contractor; supplier information; schedule information
D1, P1	CS2	Petrochemical project in the gulf coast of USA. Total procurement spends: over 200 million on national and international. Commodities included fabricated equipment, piping, structural steel (long lead items). Material needed to be ordered according to the project schedule agreed with the client and engineering progress	Detailed construction schedule was not ready; initial required-on-site (ROS) dates were estimated to drive bids and purchase orders (POs) of long-lead items; Additional labor costs in purchasing and expediting due to renegotiation with suppliers to revise *p*Os as per schedule became more defined	Early information about construction work packages (CWP) and required-on-site (ROS) dates; transparency in production schedule and progress at suppliers
D2, P1, P3	CS3	Pipeline integrity program (6–36-inch pipeline and valves) for a natural gas service provider. Valves were sourced internationally from a pre-qualified supplier list for pipes fabricated within the USA. Outage dates drive fabrication and installation	Uncertainty in need dates due to non-defined outage dates; long lead times of valves challenged the fabrication of pipes and installation schedule; changed valve source (more expensive) for specific valves due to altered need dates; original valve supplier failed to deliver as promise	Defined outage information; detailed vendor reports; status and progress of valves in production, logistics, and inventory
D3, D4	CS4	Alloy fabrication for 1000 MW combined cycle power plant in North America. The supplier was a domestic fabricator whose scope involved the fabrication and supply of pipe spools post-weld heat treatment as per specifications. A third-party inspection was required, and no material from East Asia was allowed	A large number of non-conformances identified at job-site due to material supply from East Asia; schedule deviations and subsequent quality issues to make up the schedule by the supplier	Actual status and progress information from the supplier including early quality check information
P3, P4	CS5	$3 billion petrochemical project in the Gulf Coast. European engineering and design firm had some procurement scope. U.S.- based contractor, had a lump-sum procurement and construction contract with the client. Grating fasteners initially furnished required substantial installation time and had high failure and rework rates. A new grating fastener system was introduced to mitigate the problems	Quantity breakdowns and corresponding required-on-site (ROS) dates of new fasteners were not provided to the supplier. Material stock for the product in the U.S. was zero when the first PO and ROS date were finally provided to supplier. Quantity requested in the PO was the full order amount—200,000 fasteners. This required special production runs and air freight of products from Europe	Updated construction schedule information facilitates better material planning and deliveries. Improved detail and accuracy of component/material specifications eliminate ambiguous descriptions of “commodity” items
P2	CS6	Final commissioning phase for an offshore production unit. A change in schedule made a piece of non-critical equipment into a critical package. The previous order was ineffective in meeting the requirements. The project technical team did not consult with the supply chain team (which had the global visibility of pre-approved and pre-qualified vendors) and engaged with non-qualified supplier	Non-compliance of vendor prequalification during the selection process; engaged vendor without going through the process due to lack of internal visibility (silo problem) within the organization; non-involvement of the supply chain, and accelerating order placement without prequalification	Internal collaboration and visibility: access to database of approved vendors; new vendor information and capabilities; schedule information
D5	CS7	Custom colored couplings required by the client in Asia for 3000 MV power plant project for pulverized coal piping	Schedule constraints since the piping system was installed and were waiting on couplings; the EPC shared style and quantity of couplings with the supplier but not specialty paint information despite it specified by the owner; increased lead times due to late information of custom work	Project and paint specifications shared earlier from EPC’s engineering team
C1	CS8	Time and material contract - approximately 200 million. Milestone dates with incentives and liquidated damages. Extremely schedule-sensitive project since it was one phase of a multi-phase project. The owner controlled the material flow process. The decision was made by management to bulk issue all materials to the field to expedite the start of a project, meet schedule and early milestones	Bulk and inefficient distribution of materials to the field resulted in unaccountability and loss of materials. The productivity on the field was impacted as workers were spending time searching for materials	Status, location, ownership of materials that were bulk issued

(Continued on following page)

TABLE 4 | (*Continued*) Summary of case studies supporting information needed for key supply chain decisions.

KSCDA	Case number	Project context	Problem	Information visibility needed
D2, D3, D5	CS9	Turnaround project - Increasing approximately 4,000 ft of overhead piping from 24″ 5CR to 30″ 9CR. The schedule was extremely critical since the replacement had to be completed within the turnaround schedule	The client wanted specialty alloy for the 9CR piping, which had a lead time of 7 months. The compressed schedule of the turnaround project as well as the specialty material requirement made vendor selection and meeting project requirements very challenging	Design detail and dependencies for the engineering team; potential suppliers and lead time for procurement team; handling and installation expertise for the construction team

material lifecycle. Second, neither the reviewed procurement tools nor the material tracking software has independent capabilities to cover the entire supply chain or to track all the functions. For example, some are efficient at tracking procurement at the head office while not tracking data at construction sites. As such, almost all of these tools have isolated system capabilities (procurement, cost management, scheduling, material tracking) that do not exchange data smoothly, and also their integration process is challenging. As a result, much data is transmitted manually, which is prone to error. Third, the data tracked by the tools are static and not updated synchronously based on the changes on the construction site or in the supply chain. Therefore, the data is not always as per user requirement, which affects decision-making. These findings are in line with O'Brien et al. (2004) and O'Brien et al. (2005). Nevertheless, the academic team presented the findings during the structural workshops to support the deliberations about information needs and definitions.

Finally, the mini-cases also supported the deliberations during the structured workshops. The expert panel contributed nine cases (CS1-CS9) around the ten key supply chain decision areas; some cases related to more than one decision area. **Table 4** provides an overview of the case studies. The key supply chain area related to the case is cross-indexed using the KSCDA codes. These cases included a variety of projects belonging to the industrial construction sector (oil and gas, power, mining, and metals), different sizes, and types (greenfield, brownfield, renovation). Each of these case investigations identified specific examples of the conditions that required visibility. Using the specific instances of each case, the academic team developed a general list of each decision area's information needs. This process of identifying the information needs using the mini-cases' specific information needs is explained next using the example of CS1.

4.1.3 Case Study 1

4.1.3.1 Background

The project pertains to the mid-life refurbishment of an enormous power generating facility based in North America. The project's scope included the replacement of feeder pipes, end fittings, pressure tubes, and calandria tubes.

4.1.3.2 Visibility Problems

Previous projects on refurbishment had revealed that the factors for poor project performance were a shortage, late deliveries, and quality issues of materials. Thus, it was imperative to drive the procurement of materials early; the process required setting milestone dates for items that are on the critical path far ahead of the installation dates so that these items are received and inspected onsite. This would remove a significant amount of risk of critical path items. However, numerous contractors were working on multiple projects across the nuclear refurbishment portfolio. The need to drive the procurement of materials meant having visibility into all the contractors' procurement and deliveries.

4.1.3.3 Supply Chain Decision Areas

The key supply chain decisions that can be induced from the project context are: to "identify materials and equipment requiring high visibility" since it was vital to document the items that are on the critical path for the project; and "order long-lead items and products" and "order commodity and bulks" to track the procurement and delivery of the items by the portfolio of projects and by contractors.

4.1.3.4 Information Needs

The information needs to support the three decision areas is depicted in **Figure 2**. The analysis of the interview data revealed specific information needs to support the three decision areas. For example, the decision area "identify materials and equipment requiring high visibility" is supported by project number, supplier number, purchase order issued, purchase order accepted, line items, and quantities. These information items are specific to CS1. Using these specific information instances, the academic team identified general information areas such that they are broadly applicable to challenges posed by limited visibility to make supply chain decisions. For example, the purchase order issued and accepted is categorized as purchase order information. Using these general information categories, the team documented the detailed information needed to "identify materials and equipment requiring high visibility." Examples of detailed information needs under purchase order information include shipment quantities and special handling of materials. The remaining cases (CS2-CS9) were examined by following a similar process, which resulted in the detailed information needs for all the ten decision areas. The mini-cases examination led to the identification of more than hundred information needed items across the ten decision areas for the three phases.

Following the mini-cases analysis, the academic team presented the results to the industry expert panel during the

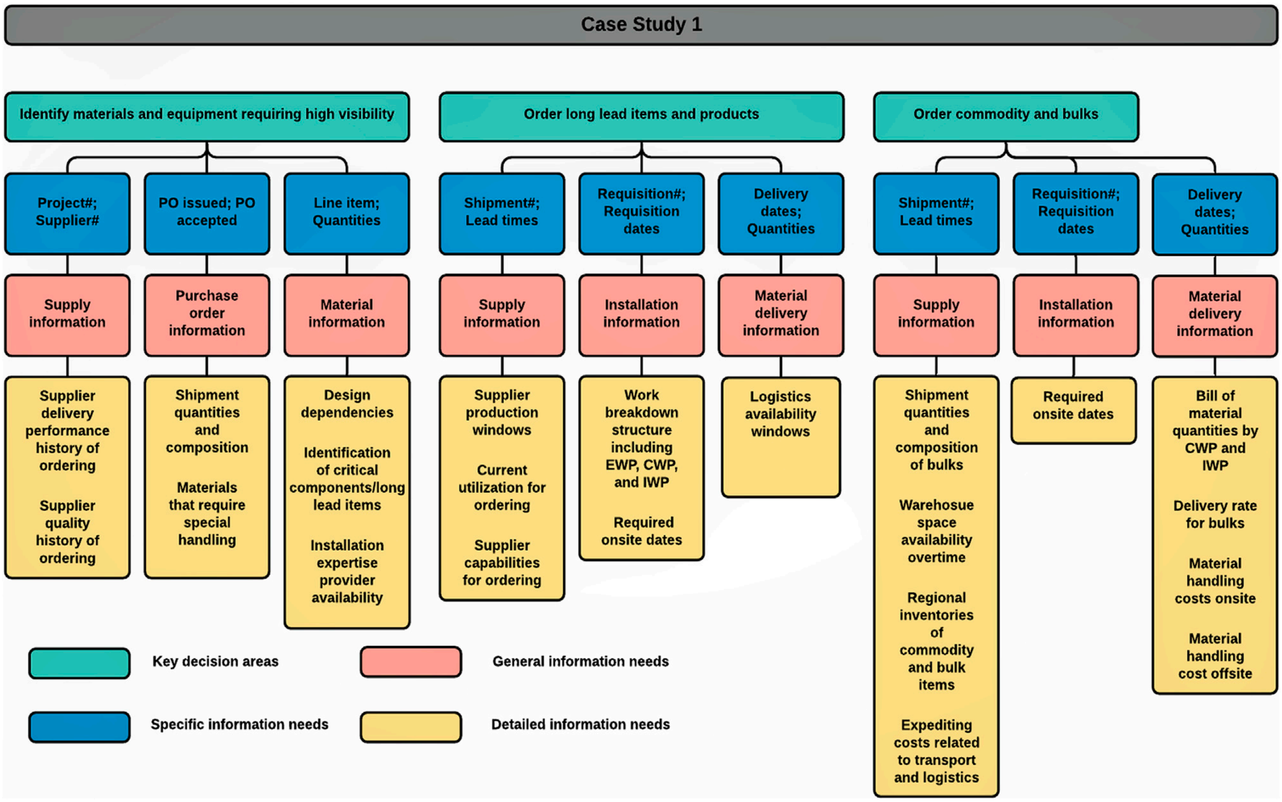

FIGURE 2 | Process of finding the detailed information needs to support key decision areas for mini-case CS1.

TABLE 5 | Information needed items and definitions for order commodities and bulk of Procurement phase (additional definitions for each phase in the **Supplementary Appendix**).

Procurement	
P4. Order commodities and bulk	
Bill of Material (BOM) quantities by CWP/IWP	Detailed BOM quantities including systems and associated assemblies, components, sub-components, consumables as per Construction Work Package and Installation Work Package
Shipment quantities and composition - bulks (gaskets, pipes, bolts, etc.)	Visibility into shipment quantities and how suppliers (and sub-suppliers) ship materials like pipes, gaskets, boltsetc.
Required-onsite/Required-at-site dates	The date needed onsite (or laydown/receiving yard) derived from the construction needed date plus the time needed to receive materials (including testing or assurance). May include a buffer between construction need date and date need to deliver to site (e.g., regulations may require a buffer)
Warehouse space availability over time	Allocation of warehouse space over time according to planned deliveries and installation of materials onsite that releases space
Delivery rates for bulks	Valuation of delivery rate for bulks to validate work package/work plans and receiving requirements
Regional inventories of common/commodity items	Information about the availability of regional inventories for common/commodity items. Used to assess the impact of a large order for bulk type materials that may exceed the suppliers' standard production capacity or stocking levels. It may be in conjunction with a frame agreement between contractor and supplier for delivery of bulk items. The availability of substitutes may also be monitored
Expediting costs related to transport/logistics	Transpiration and related costs to speed delivery of materials. This augments the cost/ability of the supplier to accelerate production
Availability level/options of alternate supply source for common parts/ consumables	Alternate supply of common parts that can substitute for parts that are ordered (i.e., can substitute an alternate if the desired is unavailable)
Materials handling costs offsite	Costs for materials handling, including storage costs offsite
Materials handling costs onsite	Costs for materials handling, including storage, re-handling, and maintenance costs onsite

structured workshops. In the workshops, the panel systematically reviewed each information need, modified it, and developed a detailed definition. This process involved checking the following: 1) if the information needed was indeed due to lack of visibility and not a project constraint/condition (e.g., country of origin requirements), or benefit/outcome of having good visibility (e.g., transparency using near-real-time access); 2) if the information needs were not broad or unclear (e.g., quality performance of suppliers); 3) if the decisions of the specific mini-case were supported by other information needs that were not apparent in the case; 4) if the information needs supported multiple decision areas; and 5) the definitions of the information needs were detailed and included perspectives from all: the owner, engineer, contractor, supplier, and technology vendor.

The entire process included multiple rounds of review and refinement. The reduction and finalizing of information needs and definitions took several workshops until there was collective consensus by the entire team. In the end, the team identified seventy-nine information needs across the ten key supply chain areas. **Table 5** shows a sample by listing the ten detailed information needs and respective definitions that support the key supply chain area "P4: Order Commodities and Bulk." The full set of information needs and definitions for the remaining nine decision areas are given in the **Supplementary Appendix**.

4.2 Evaluation

The next phase of the research process comprises evaluating the credibility, transferability, dependability, and applicability of the decision areas, associated information needs, and definitions. The evaluation was conducted using the internal team, an external expert team, agreement between internal and external team, and case studies.

4.2.1 Team Evaluations and Agreement

Team evaluation included both the internal and external team evaluating the results of the study. This process involved checking each decision area, information needs, and definitions for quality, usability, and confirmability. This step also increased the content and construct validity of the research results. Five of the external participants also pointed out that the information needs and definitions can be used to audit their respective firms to get a snapshot of their current level of visibility on projects. Some of the external team members were curious about the research process that led to the identification and definitions of the information needed items. When explained, all of the seven external teams agreed that the use of multiple case studies as beneficial. As per them, the nine cases being complex in nature produces insights that can be applied to projects of equivalent and lesser complexity. Overall, the participants (internal and external) indicated that the research findings to be of high quality, complete in terms of information content required to support decision making on projects, and applicable in practical contexts within the industrial construction sector.

In addition, both groups also rated the importance of the information needs and definitions using the 4-point Likert scale. The Kendall's Coefficient of Concordance results indicates a high level of agreement between the two groups on the rankings of the information needs ($W = 0.885$, Chi-Square = 137.986, df = 78, p-value < 0.0001).

4.2.2 Evaluation Using Case Study

The project investigated is a multi-billion-dollar oil and gas project in Canada. The case starts with the project background and an overview of the supply chain. Next, the visibility measures that were put in place are discussed. The analysis starts with identifying the decision area(s) critical to the case and the available supporting information, as well as comparing the identified decision area(s) and the information of the case with the set of decision area(s) and information needs from the research findings.

4.2.2.1 Project Background and Supply Chain Overview

The goal of the project was to boost the oil production in a region. The project involved the mining and extraction process of bitumen and scope of work included mine and site development, ore preparation plant, extraction, tailing and froth treatment facilities. The project had a cost-plus contract and an engineer-procure-construct (EPC) project delivery method. The supply chain of the project is depicted in **Figure 3**. The materials for the project were fabricated in multiple fabrication plants based in Asia. These included pre-fabricated small modules, stick-built, and bulk materials which were transported in 40-inch containers to the port in Asia. It also included pipe spools and steel that were part of a big module assembly program. All the materials were shipped to North America by sea. At the North American port, the materials traversed through different locations before reaching the project site for installation. First, the stick-built materials were transported by trailer trucks to a central staging yard. The smaller modules were transported directly to the project site for installation using trailer trucks. The other pre-fabricated and bulk materials were transported via rail to the central staging yard. The pipe spools and steel required for the big module assembly were transported to the staging yard and then to multiple modular yards managed by different contractors. Once assembled, these big modules were transported using heavy trailer trucks to the jobsite for installation. Bulk and ship-loose materials required for the module assembly were transported separately to the modular yards. The remaining materials that were part of the stick-built construction process were shipped directly to the site. This project was fast-tracked, and the modular assembly program was on the critical path of the schedule and consisted of more than 1,000 module packages.

4.2.2.2 Visibility Problems

Since the supply chain included multiple fabricators, ports, staging yard, laydown facilities, and warehouses (some even share between contractors), the information exchange process required a lot of cross-scope coordination involving the EPC, multiple contractors, and fabricators. The EPC's material management system lacked consistent and accurate data since there were at times voids of information material due to the unavailability of timely and accurate information from international vendors in the supply chain. There was missing information related to pipe supports and other bulk materials since the EPC did not load and track the relevant data in their material management system. In addition, it was a challenge to aggregate all the data and compile them for reporting purposes since all these stakeholders (five fabricators and four modular yards) had their own material management system and process. Next, the project included numerous heavy haul shipment coordination. Heavy haul items are materials that require a specialized over-sized trailer to transport materials that exceed certain dimension—length, width, height, or weight

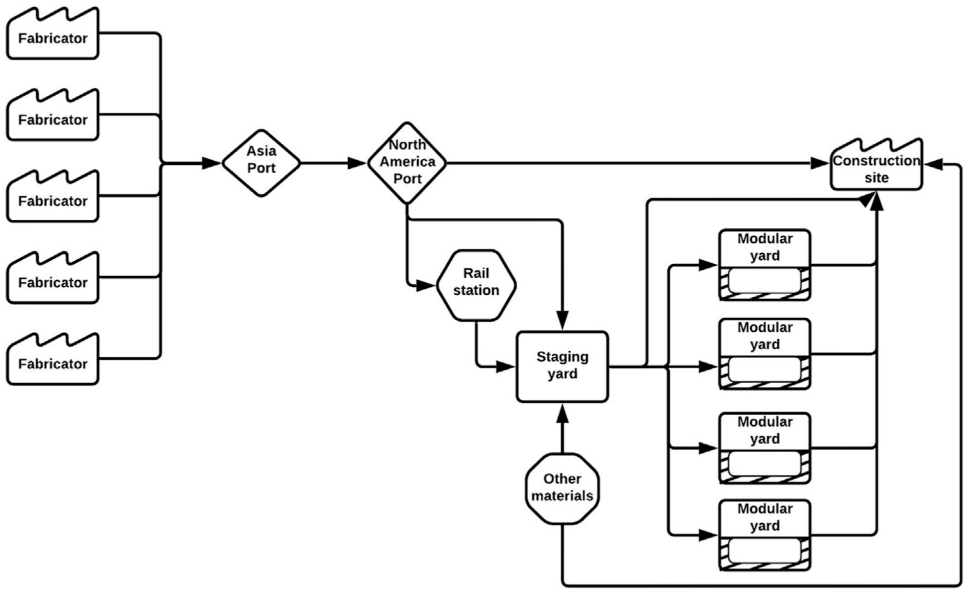

FIGURE 3 | Overview of the supply chain.

– or involves non-typical loading pattern. Each heavy haul shipment requires special coordination and permitting actions both on-site and throughout the supply chain process. The logistics carrier has to adhere to the regulations of any port of call, municipality, and transit authority involved in the transportation of the heavy-haul item. For example, small towns might have to close off their main streets or temporary closure of roads and bridges for a large heavy haul item to pass through. Last but not the least, the complex international supply chain made it difficult to track the disruptions of steel and pipe in the supply chain. All these highlighted problems resulted in an inefficient and cumbersome data-exchange. This, in turn, led to reactive decision-making based on outdated and static material information. In other words, there was a lack of visibility regarding materials at different points across the supply chain. For example, there was lack of owner visibility into challenges of materials readiness and workface planning across the multiple contractors giving rise to cost and schedule uncertainty.

4.2.2.3 Visibility Measures on the Project

Owing to the criticality of the modular assembly program, the owner mandated that the project pipe spools and steel piece-marks be barcoded and tagged using RFID. The application of these material tracking technologies was conducted at the port in Asia. The supply chain was also adjusted to enable a smooth material flow. In fact, the central staging yard was constructed in Canada to support the module assembly program. The project's supply chain process involved loading materials in removable racks in Asia by grouping them by modules. The packing list of the racks of materials were digitally created after physically scanning the materials into shipping containers, and the packing was done by work packages. After arrival in Canada, the racks were stored in the staging yard in Canada and shipped to the modular yards based on the material withdrawal request by the respective yards.

4.2.2.4 Analysis and Discussion

The expert panel reviewed the case study. The panel agreed that the module assembly installation could impact the schedule due to disruption of materials in the complex international supply chain. As such, the application of material tracking technologies was warranted. The system provided shipment data at the item and tag level to account for material flow disruption. Nevertheless, the panel perceived that the project needed more information about the following aspects.

First, there was no information about the modules after they were issued to construction. It would be helpful to know when and how many of the modules were installed in comparison to the construction need dates and purchase order (PO) quantities or bill of material (BOM) quantities. The construction need dates depend on the path of construction and differ by material types (long lead vs. bulks). Thus, identifying the long-lead items, the path of construction, shipment quantities and composition for engineered materials and major equipment packages is vital. Furthermore, information about constraint-free installation of the modules would provide visibility into quantities installed. These can be compared with either the PO or BOM information.

Second, the pipe supports and some bulks were not tracked using the materials management system. As per the panel members, pipe supports and bulks play an essential role in module installation. Therefore, visibility into shipment quantities and composition, warehouse space, delivery rates, and regional inventories, and expediting costs for bulks was required. This is especially important to plan for unplanned rush order of bulks if required at the later part of the project.

Third, the panel recognized that any delays in the project's progress and communications in the supply chain could result in

TABLE 6 | Information available/needed for the project and associated decision areas.

KSCDA	The information needed for the project	Definitions
D1	Upstream constraints at fabrication facilities	Visibility into constraints in the fabrication yard release dates, modular yard schedule, fabrication yard, and tier-2 supplier contractual milestones
	Construction sequence/path of construction	The general plan for construction sequencing, including work areas that supports plan for Construction work packages (CWPs)/Installation work packages (IWPs)
	Current fabricator lead times for early planning	Current windows between ordering and delivery for components. May include sub-tiers of suppliers (upstream) for clarity
	Logistics availability windows	Shipping window/logistics constraint; e.g., limited availability of the heavy-lift capability
D2	Identification of critical components/long lead time items	Critical/long-lead components are identified through a review of Required-at-site (RAS) dates against purchase order (PO) lead times; such components require early ordering to assure timely delivery to site. Critical/long-lead components set key procurement dates and may require extra monitoring. Critical components may also be identified as ones that have specific site installation dates that come from contractual milestones or key constraints such as limited availability of installation/expertise providers, weather windowsetc.
D3	Shipment quantities and composition - engineered materials, major equipment packages	Visibility into shipment quantities as well as how suppliers (and sub suppliers) ship materials (e.g., major equipment, packages of equipment including sub-assemblies and parts. Also, loose components, spares, etc. of equipment that is designed and shipped by vendor)
P1	Required onsite dates	The date needed on site (or laydown/receiving yard) derived from the construction needed date plus the time needed to receive materials (including testing or assurance). May include a buffer between construction need date and date need to deliver to site (e.g., regulations may require a buffer)
	Logistics availability windows	Shipping window/logistics constraint; e.g., limited availability of the heavy-lift capability
P3	Construction need dates	Installation date for materials on-site based on current information (Path of construction, schedule level of detail)
	Supplier production schedule	Supplier production plan and schedule (including incremental milestones) - constraints; cutting, welding, fit up, inspection etc.
	Finished goods inventory levels offsite	Stock level of finished goods off-site at various supply chain nodes
	Finished goods inventory levels onsite	Costs for materials handling, including storage, re-handling, and maintenance costs on-site
	Logistics availability windows	Shipping window/logistics constraint; e.g., limited availability of the heavy-lift capability
	Delivery rates for bulks	Valuation of delivery rate for bulks to validate work package/work plans and receiving requirements
	Regional inventories of common/commodity items	Information about availability of regional inventories for common/commodity items. Used to assess the impact of a large order for bulk type materials that may exceed standard production capacity or stocking levels of the suppliers. May be in conjunction with a frame agreement between contractor and supplier for delivery of bulk items. Availability of substitutes may also be monitored
	Expediting costs related to transport/logistics	Transpiration and related costs to speed delivery of materials. This augments cost/ability of supplier to accelerate production
C1	Status and location of modules/materials in the supply chain at the tag and item level	Near real time transactional information (status and location) of physical material as it traverses through different supply chain nodes as appropriately planned for the project (includes desired upstream nodes such as fabrication shops and 2nd tier suppliers; specification of extent of tracking is part of project planning). Must include BOM information for parent-child assemblies. Tags may need to be assigned upon receiving if common parts are shipped in quantity (bag and tag)
	Laydown space availability in staging yard, modular yards, warehouse over time	Allocation of laydown/warehouse space over time according to planned deliveries and installation of materials on-site that releases space
	Supply chain's ability to hold inventory and delay deliveries	Ability of a supplier or logistics yard to hold additional inventory or delay deliveries. This can relieve the pressure on site storage needs. May be contractual
	Client milestones	The dates set by client for key activities (e.g., start dates, turnaround windows, and required completions)
	Bill of material quantities	Detailed bill of material quantities including systems and associated assemblies, components, sub-components, consumables as per CWP and IWP.
	IWP readiness including design, materials, labor, equipment etc.	Visibility into IWP readiness to assure they are constraint free

unplanned stockpiles of materials. Therefore, visibility into orders at offsite and onsite location, checking the ability of supplier/fabricator to delay deliveries and/or of storage spaces (laydown, warehouses) if they can hold additional inventories is essential for effective inventory management. Fabricator's/supplier's ability to delay or hold deliveries, in turn, require information about upstream constraints, lead times, and production schedule of fabricators/suppliers.

Lastly, the panel commented that scope changes or change orders could impact the project. So, for the module program's success, the panel recognized that the project needed to manage constraints by continuously reviewing look-ahead schedules. Incase constraints are not met, then the project will have to expedite, recover the schedule, and readjust sequence to ensure timely and accurate delivery of materials. Constraint management, expediting, recovery, and re-sequencing are all part of the decision area C1- 'adjustment in schedule and/or supply chain to accommodate the material flow disruptions. The information required to support this decision area include readiness of installation packages, client milestones, status and location of modules and materials in the supply chain, BOM quantities, and supply chain's ability to hold or delay inventories. The above discussed information needs, their definitions, and the relevant decision area(s) are provided in **Table 6**. **Table 6** is a subset of broader research findings of this study. This suggests that the case study is a good test of the decision areas and information needs.

The internal expert panel discussion revealed that the research findings provide a set of information needs and definitions which can be used in determining the information that is possible from the available data or the data conversion required using definitions that can facilitate a more efficient data exchange process. In other words, it can aid information to support decision making. For example, the material arrival and departure times (commonly tracked) can be used to calculate the inventory level of materials and space availability at supply chain locations. This information can be used to plan the delivery of modules from the Asia port as well as to ensure an effective inventory management in the staging area. This, in turn, can improve productivity in laydown yards and during installation and reduce both procurement and inventory costs. Thus, the applicability of the research findings in a real-world context indicates the practical value and use of decision areas and information needs.

5 CONCLUSION

Having visibility into the supply chain can result in more effective management and improved project performance. However, the construction literature lacks the definition of the detailed information needs in the supply chain that supports decision-making and enables visibility. This study developed and defined the detailed information to support key supply chain decision areas during detailed design, procurement, and construction phases for a typical industrial construction project.

The study contributes to the body of knowledge in two ways. First, the study defines ten key decision areas and 79 detailed information needed items, representing a significant advance to our understanding of information. This work was undertaken from the perspective of supporting decision making; development was performed by knowledgeable professionals as well as academics. The definitions are considerably more detailed and comprehensive than prior work in the area, whether from the perspective of academic literature or embodied in industry information tools. The input of multiple stakeholder types (owner, contractor, designer, supplier/technology provider) contributed to the quality of the definitions. Thus, the definitions collectively provide a unifying framework with a common vocabulary in the construction supply chain domain.

The second intellectual contribution is methodological. The study describes a rigorous process that can be used to develop detailed definitions of visibility. Many prior definitions of visibility in the general supply chain management and logistics literature have been conceptual. Other efforts are typically inductive from limited cases or deductive from first principals, but not both. This study describes both a deductive and inductive approach that uses the expertise of both academics and industry subject matter experts. While all of these elements have been seen in prior research, combining them to develop not just research findings but also practical definitions represent an advance for construction and related applied research.

The study also has practical implications. The set of information needs and definitions contributed by the study represents the user's desired information that is not fully available today. Therefore, the set of decision areas and information needs can be used by practitioners to augment their tools and procedures to better support projects. For example, the identified information needs and their definitions can be used to draft contracts along the lines of information needs on projects; this inclusion can help set expectations regarding information exchange between project participants early on during projects. Also, the information definitions can be used as a starting point to develop standardized definitions and needs statements that can help drive technology vendor implementations. Furthermore, practitioners can use the definitions as a common language to communicate with other stakeholders in the supply chain. The case study of industrial project used for evaluation in the current study gives some insight into how the definitions could be used in a real-world context.

This study provides an advance to our understanding and provides the groundwork for further research. One limitation of the current study is that the group of subject matter experts is based in North America and evaluation in other locations would help to generalize the findings. Similarly, the findings are centered in industrial construction and expansion to other sectors would be a worthwhile endeavor. That said, a focus on supporting decisions likely drives a set of information needs that is broadly applicable, particular for projects with complex supply chains as in the industrial sector. Second, while nine industrial construction project case studies contributed to the development of the research results, the study used a single case project to evaluate the research findings. Future research should investigate multiple case projects within industrial construction sector under different conditions to improve generalization and validation of the research findings. Another avenue of future work is using the defined information needs and supported decision areas as an evaluation framework of the SCV process. To achieve this, one way would be to identify the relevant SCV measurement variables for construction and using them to quantify the information needed items and decision areas. Quantification of the information items can also help in assessing the contribution of the individual information needs to the respective decision areas and to the overall SCV process. Beyond further expansion and validation of the findings, future research can utilize the definitions for more detailed assessment of supply chain visibility as well as a foundation for technical development. Similarly, practitioners can use the research to assess the limitations of their existing systems and prioritize augmentation using the research. Overall, the authors expect this research will be foundational in the development of more capable construction supply chains.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Institutional Review Board at The University of Texas at Austin. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Combining decentralized decision-making and takt production in construction planning and control to increase production flow

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Takt production and decentralized decision-making have been recent areas of interest in (lean) construction management research. Both have the potential to improve flow and contribute to increased production performance. Despite the interest, the efforts toward decentralization have not effectively considered the first-line workers; simultaneously, takt production studies suggest that neglection of workers' involvement has led to implementation challenges and hampered flow. Thus, combining decentralized decision-making (including the involvement of the first-line workers) and takt production could have the potential for further improving production flow and performance. By utilizing design science research, this explorative single-case study aimed to evaluate the effect of decentralized decision-making and takt production to production flow through formulating, implementing, and validating a decentralized takt production framework. The primary data were collected from three production planning sessions and 17 semi-structured interviews, supported by site observations, resource tracking data, schedule data, cost data, and production progress reports. The framework formulation and validation were also supported by six expert workshops. The findings indicate that decentralization can be combined with takt production, aiding production flow. Good operations flow was especially aided by decentralized decision-making. These positive effects were supported by observations of improved utilization of site teams' knowledge in planning, better commitment, communication, team-building process, and positive competition between teams. In addition, 23% duration savings were achieved in the production phase in which the framework was implemented. Also, stable resource utilization of trades was achieved. The decentralized decision-making practices were successfully implemented in the planning phase; however, the elements of decentralization were not adequately utilized in the control phase, resulting in the intended benefits not being obtained to their full potential magnitude. An extensive effort over single projects and organizations would be needed to gain all the intended benefits, while the competence to successfully operate with (decentralized) takt production increases with experience. The study makes scientific and managerial contributions to improving construction production planning and control practices and flow by exploring the combination of decentralized decision-making and takt production and by considering site teams and first-line workers' viewpoints, which have been scarce in previous research.

KEYWORDS

construction management, production planning and control, decentralization, takt production, production flow, design science research, case study

Introduction

Takt production has been increasingly studied in construction management research over the last decade. Takt production is a location-based production planning and control[1] (PP&C) method, aiming to increase production flow by considering the effective utilization of space in construction sites and adopting insights from the most prominent lean construction and lean manufacturing best practices (e.g., Frandson et al., 2013). In lean, the focus is on performing actions just-in-time (JIT), advocating built-in quality, building standardized and low-variability processes, and continuous improvement with the high inclusion of people (Liker, 2005). Following these practices, takt production operates by planning tasks and resources to proceed at a consistent beat, "takt," that matches the client's demand (takt planning), steering the production as deviations or problems arise to maintain the beat (takt control) (Dlouhy et al., 2016), and continuously improving the system (Lehtovaara et al., 2021). Takt production is a potential way to increase production flow, efficiency, and production performance. The documented benefits include significant production duration reductions (Frandson et al., 2013; Binninger et al., 2018), improved quality, safety (Heinonen and Seppänen, 2016), and worker productivity (Kujansuu et al., 2020), with increased transparency of communication and production control effectiveness (Linnik et al., 2013). These benefits have been documented even when implementing takt production for the first time, with no prior experience utilizing the method (e.g., Lehtovaara et al., 2019).

Another research stream that has recently shown potential in improving construction production performance is the decentralization[2] of decision-making in PP&C processes. In construction, the mainstream PP&C methods (such as the critical path method, CPM; Plotnick and O'Brien, 2009) have assumed that production can be successfully managed through central and hierarchical decision-making. However, the truthfulness of this assumption has long been questioned (e.g., Johnston and Brennan, 1996). Decentralized, autonomous decision-making has gained broad interest in the project, organization, and production management domains, demonstrating benefits such as increased efficiency, creativity, and well-being of workers in, for example, the military (McChrystal et al., 2015), manufacturing (Liker, 2005), and healthcare (Laloux, 2014). In construction, decentralization of PP&C has been promoted, particularly in the context of lean construction, through methods such as the Last Planner® system (LPS, Ballard, 2000), yielding promising results for increasing production performance (Castillo et al., 2018). LPS has also been utilized in parallel with other PP&C methods to improve collaboration. Indeed, the combination of CPM and LPS (Huber and Reiser, 2003), the location-based management system (LBMS) and LPS (Seppänen et al., 2010), and takt production and LPS (Frandson et al., 2014) have all shown promising results in bringing synergies to each other while emphasizing decentralization.

Despite the interest in decentralization in construction, the efforts to decentralize PP&C have not effectively considered the first-line workers but mainly focused on collaboration between managers and crew leaders (Lehtovaara et al., 2022). This is surprising as considering workers' input when forming a plan, involving them in controlling the production, and nurturing continuous improvement through their ideas is at the heart of lean in manufacturing (e.g., Liker, 2005). Several takt production implementation initiatives suggest that neglecting workers' involvement has led to implementation challenges, hampering flow (e.g., Vatne and Drevland, 2016). Decentralized decision-making could be especially suitable in takt production, as takt planning requires an early, detailed understanding of the production process that site crews and especially workers possess. Moreover, takt control calls for immersive involvement of all site personnel to act on the emerging issues on time and learn from them while keeping production on track (Lehtovaara et al., 2021). However, combining takt production with decentralized decision-making involving first-line workers has not been previously studied.

Therefore, it could be argued that if the possibilities of decentralization (including the involvement of the first-line workers) were considered when implementing takt

1 Being a vital part of production management, PP&C processes determine what and when to produce and how to control the production in a way that achieves the initiated plan (Vollmann et al., 1997). While planning gives a structure for the production's progress, control is needed to keep the production on track in the event of something unforeseen happening.

2 Decentralization denotes a process by which the decision-making responsibility is shared from an authority to lower levels of the hierarchy (Mintzberg, 1983). In construction PP&C, decentralization could be realized as dispersing the planning and control authority from the project and site managers to site teams, comprising trade crew leaders and workers.

production, the potential of takt production in aiding flow could be further increased. An interesting research avenue emerges from these premises, allowing us to formulate the research question (RQ) for this study: *how could combining takt production with decentralized decision-making affect construction PP&C practices and production flow?* To answer the RQ, we employ a design science research (DSR) approach to formulate, implement, and validate a PP&C framework that allows evaluating the effect of decentralized takt production on production flow. The framework is implemented in an industrial construction project in central Finland, where an existing manufacturing plant was extended with a new warehouse building, consisting of ~10,000 m^2 of space. The implementation targets the interior phase of the project, especially the mechanical, electrical, and plumbing (MEP) work. The study is limited to the interior phase of a building construction project to sharpen its focus. This is an explorative study that, by utilizing qualitative and quantitative evidence, aims to provide insights into how decentralized takt production could affect construction production flow and production management practices.

Theoretical background

Construction production flow and takt production

Flow plays a vital role in achieving robust performance in any production process. Production flow can be understood as a transformation of materials into products as they move through a value stream, where a series of value- (and non-value-) adding actions are performed (Rother et al., 2003). Good flow occurs when the transformation across the value stream occurs swiftly and evenly (Schmenner and Swink, 1998), with few non-value-adding actions (Womack and Jones, 2003). Specifically, production flow can be inspected from two different but intertwined perspectives: process and operations flows (Shingo and Dillon, 1989). In construction production, process flow denotes the flow of sequenced activities performed in a single location (e.g., an apartment), while operations flow means the flow of a single activity performed by a trade crew in different locations (Sacks, 2016). Sacks (2016) distinguishes the elements of good flow in a construction project's production: the first eight elements (P1–P8) are related to process flow, and the latter two (O1–O2) refer to operations flow:

- P1: (process flow condition 1): The variation of takt times[3] across locations is minimized.
- P2: The batch size (the number of locations occupied by a trade crew) is minimized.
- P3: The sum of time buffers between activities is minimized.
- P4: The number of unnecessary activities is minimized.
- P5: The amount of re-entrant[4]f flow is minimized.
- P6: The amount of rework is minimized.
- P7: The amount of making-do is minimized.
- P8: The amount of work in progress (WIP) is minimized.
- O1: (operations flow condition 1): The variation in each trade crew's takt time is minimized.
- O2: Set-up, inspection, and non-value-adding times are minimized.

Effective PP&C methods play a fundamental role in achieving good flow (e.g., Koskela, 1992; Liker, 2005). In construction, various methods have been implemented to achieve this objective; in particular, the so-called location-based planning and control methods (e.g., line of balance; Pe'er, 1974; and LBMS) have been implemented and proven to contribute positively to flow (e.g., Olivieri et al., 2018), compared to widely used, activity-based methods (such as CPM), which do not effectively consider the utilization of space and mostly neglect the role of flow. Location-based planning is akin to space planning, which both consider locations as critical resources (Akinci et al., 2002). Furthermore, spatiotemporal planning methods have been developed that use algorithmic and graphical approaches to ensure smooth utilization of locations and resources; these have also been conceptually examined with takt production (Francis et al., 2019).

In contrast to other location-based methods, whose primary aim has been to enable steady operations flow, in takt production, the aim is to increase process and operations flows simultaneously, making it a prominent candidate to achieve all ten elements of good flow. In practice, the most notable difference between takt production and other location-based methods is the prioritization of standby capacity buffering over time and space buffers, supporting timely and reliable handoffs (Frandson et al., 2015) and thus the flow of processes. Indeed, takt production has been perceived as positively affecting overall production flow (e.g., Linnik et al., 2013). Dlouhy et al. (2017) also argue that takt production could provide additional synergies for industrial construction, in which interlacing construction and equipment installation phases allows faster and more reliable handovers, increased overall project flow, and reduced overall project duration. Lehtovaara et al. (2021) have observed that implementation maturity also

3 In construction, takt time refers to the required duration for completing a certain activity in a given location to match the client's needs (Dlouhy et al., 2016).

4 Re-entrant flow occurs when a trade crew needs to access a work location multiple times at different process stages (Brodetskaia et al., 2013).

affects results; in cases where takt production is implemented with no prior expertise, it has contradictory effects on operations flow (negative effects being such as increased resource fluctuation), but with increased experience, the results for both process and operations flows are primarily positive.

Takt production implementation consists of three predominant steps (adopted from Lehtovaara et al., 2021): takt planning, production ramp-up and takt control, and continuous improvement.

Takt planning

In takt planning, the aim is to create a production plan that employs balanced process and operational flows. The process begins by addressing the client's needs for production that form the basis for initiating flow (Frandson et al., 2013) and by collecting relevant production data as the basis for planning (e.g., including a list of production tasks, their sequence, estimated production rates, location-based quantities, available resources, deadlines, and other priorities). The plan is further developed by increasing the level of detail. These planning horizons are formed similar to the planning horizons of LPS (e.g., Ballard and Tommelein, 2021). The planning process consists of iterating several planning parameters: size and form of locations (takt areas) where a batch of activities are simultaneously conducted, work packages that contain the batch of activities (takt wagons), the time in which the batch of activities should be completed in a single takt area (takt time), and resourcing (Binninger et al., 2017). The plan is further balanced by integrating capacity, inventory, and time (Hopp and Spearman, 2011), and plan (Frandson et al., 2015) buffers into the plan to cope with production variability. Takt planning especially contributes positively to flow elements P1–P4 and P8 (Lehtovaara et al., 2021).

Production ramp-up and takt control

During production ramp-up, the production pace is set, and the initial emerging problems are solved. More time for work in the first takt areas can be planned to ensure a "soft" start and additional time to solve unforeseen problems during ramp-up. Takt control itself aims for timely, short-cycled, and visual production management, with an emphasis on effective quality control (Dlouhy et al., 2016). In takt control, the primary aim is to achieve stable handoffs for every wagon, where problems are immediately identified and solved before the next wagon's activities begin (Frandson et al., 2015). Takt control requires more effort at the beginning of production. Later on, it has been reported to result in increased process and operations flows, especially contributing to flow elements P5–P7 and O1–O2 (Lehtovaara et al., 2021).

Continuous improvement

Continuous improvement in and across projects is necessary to increase production flow over time and reduce the effort needed in subsequent projects' takt planning and control phases. Takt production makes emerging problems highly visible and creates an urgency to solve them. Addressing them requires an increased effort at first but offers an opportunity for effective production system improvement in the long term (Lehtovaara et al., 2021).

Decentralized planning and control

The decentralization of planning and control has produced multiple benefits in various domains and industries. These benefits include enhanced project performance; increased capability for skill development; better performance in conflict situations (Humphrey et al., 2007; Yang and Guy, 2011); and increased proactivity, commitment, creativity, motivation, and well-being of workers (Mintzberg, 1983; Richardson et al., 2002). In the construction PP&C context, the observed benefits include greater process transparency, improved plan reliability, reduced dependability on individual leaders, and reduced waste (Priven and Sacks 2015; Lehtovaara et al., 2022), with a positive contribution to project time and cost performance (Castillo et al., 2018).

Despite these benefits for projects and project personnel, decentralization has also been perceived as having disadvantages compared to centrally led management practices. Koskela et al. (2019) also argue that an appropriate combination of centralized and decentralized approaches often offers the best solution instead of opting for only one. With inappropriate balance, decentralized practices might result in inconsistent coordination and communication between teams (Stinchcombe and Heimer, 1985), hampered information flow and knowledge sharing (Mintzberg, 1983), and excessive risk-taking (Lanaj et al., 2013), especially in instances with a high degree of complexity and a large number of interdependent teams (Leavitt, 2005).

To successfully implement decentralized planning and control while avoiding possible disadvantages and considering the first-line workers, the following drivers have been suggested in previous studies:

- Ensuring early and intense involvement of site teams, officially determining their responsibilities in decision-making, and allocating adequate time and resources for individuals' decision-making and problem-solving through the production (Chinowsky et al., 2010; Saurin et al., 2013; Lehtovaara et al., 2022)
- Training teams and individuals to cope with their increased role in decision-making and supporting managers to act as facilitators rather than autocrats (Bertelsen and Koskela, 2005; Pikas et al., 2012; Saurin et al., 2013; Lehtovaara et al., 2022)
- Initiating trust and transparency between site teams and individuals through team-building and mutual access to

information flow (Howell and Ballard, 1998; Baiden et al., 2006; Chinowsky et al., 2010; Lehtovaara et al., 2022)
- Empowering site teams and individuals for autonomous decision-making in practice while building cultural change toward a broader recognition of decentralization (Saurin et al., 2013; Magpili and Pazos 2018; Pryke et al., 2018; Lehtovaara et al., 2022).

Based on the literature, it seems that takt production could be suitably combined with decentralized decision-making to achieve increased flow. The approaches have several complementary points, and the decentralization drivers could possibly be embedded in the takt production process. For example, greater process transparency and improved plan reliability are necessities for successful takt production, needed in every implementation step. Intense involvement and training of site teams would support learning the requirements of takt production, while individuals would be better committed to executing the plan. Encouragement for autonomous decision-making can also help better utilize the site teams' knowledge in the process and reduce the workload of managers, which often increases in (first) takt implementation initiatives (e.g., Lehtovaara et al., 2021). In the following sections, we examine how the combination of takt production and decentralized decision-making can be realized in practice.

Materials and methods

Research strategy

We employ DSR as a research strategy, which allows us to answer the RQ by formulating, implementing, and validating a decentralized takt production framework. In DSR, the researcher takes an active role as a problem-solver instead of a sole observer, enabling an in-depth, meaningful reflection on the observed phenomena (Holmström et al., 2009). In this study, DSR comprises four phases, guided by Kuechler and Vaishnavi's (2008) approach: 1) problem definition and presentation of relevant literature (already presented in the introduction and theoretical background sections); 2) formulation of a framework and case study preparation; 3) implementation and validation of the framework; and 4) discussion of the findings and formulation of the study conclusions.

A case study was chosen as a primary research method. A case study allows drawing conclusions from a complex issue while inspecting it in a real-life context through an element of substantial narrative (Flyvbjerg 2006). Moreover, a single-case study approach was chosen to gain focus and depth in data collection and analysis. Tellis (1997) (p. 3) points out that a single-case study is especially suitable for "revelatory cases where an observer may have access to a phenomenon that was previously inaccessible" and is thus ideal for exploring decentralized takt production. The flow of the study is presented in Figure 1 and further elaborated in the remainder of this section. The process for formulating and validating the framework through expert workshops is presented on the left side of the figure, while the case study process is presented on the right side.

Framework formulation and validation: Expert workshops

The study was conducted as part of a larger Finnish research project, in which a consortium of 21 companies and a university research group (Lavikka et al., 2020) explored the application of decentralized PP&C to construction production. To aid in formulating the framework, preparing the case study, and validating the results, six expert workshops (that were part of the research project) were held as a supporting research method. A workshop is a qualitative research method that can be used to gain feedback and insights on novel phenomena, such as process or product innovation, through interactive group sessions (Thoring et al., 2020). Facilitated workshops with domain experts are often conducted when an explorative touch and various viewpoints are needed regarding a scarcely studied topic to provide insights for evaluating initially formed ideas (Ørngreen and Levinsen, 2017).

In total, six expert workshops were conducted with representatives of general contractors, construction management consultants, design consultants, trade contractors, and software developers who were invited by the companies participating in the research project. In our study, an expert is defined as a person with domain knowledge of construction management and an interest in developing construction PP&C practices. Participation was not restricted by years of experience or employment title to allow a broader discussion with a wide range of opinions. Approximately 30 experts participated in each workshop (the number slightly varied between sessions). The same base pool of participants was maintained throughout the study to enable them to form a shared mindset and achieve a safe space to exchange insights and accumulate learning over the course of the sessions (Race et al., 1994).

The workshop structure, themes, and their relation to the case study are presented in Figure 1. The workshops were embedded in bi-monthly, half-day research workshops, which were arranged specifically to explore the application of decentralized PP&C. The authors served as facilitators, actively participating in the discussions. The session lengths were 60 min in sessions 1, 2, and 6 and 30 min in sessions 3, 4, and 5. The discussion was mainly held within the whole group but occasionally broken into smaller groups to enable each attendee's active participation (Ørngreen and Levinsen, 2017). We took notes from the discussion, and insights were also

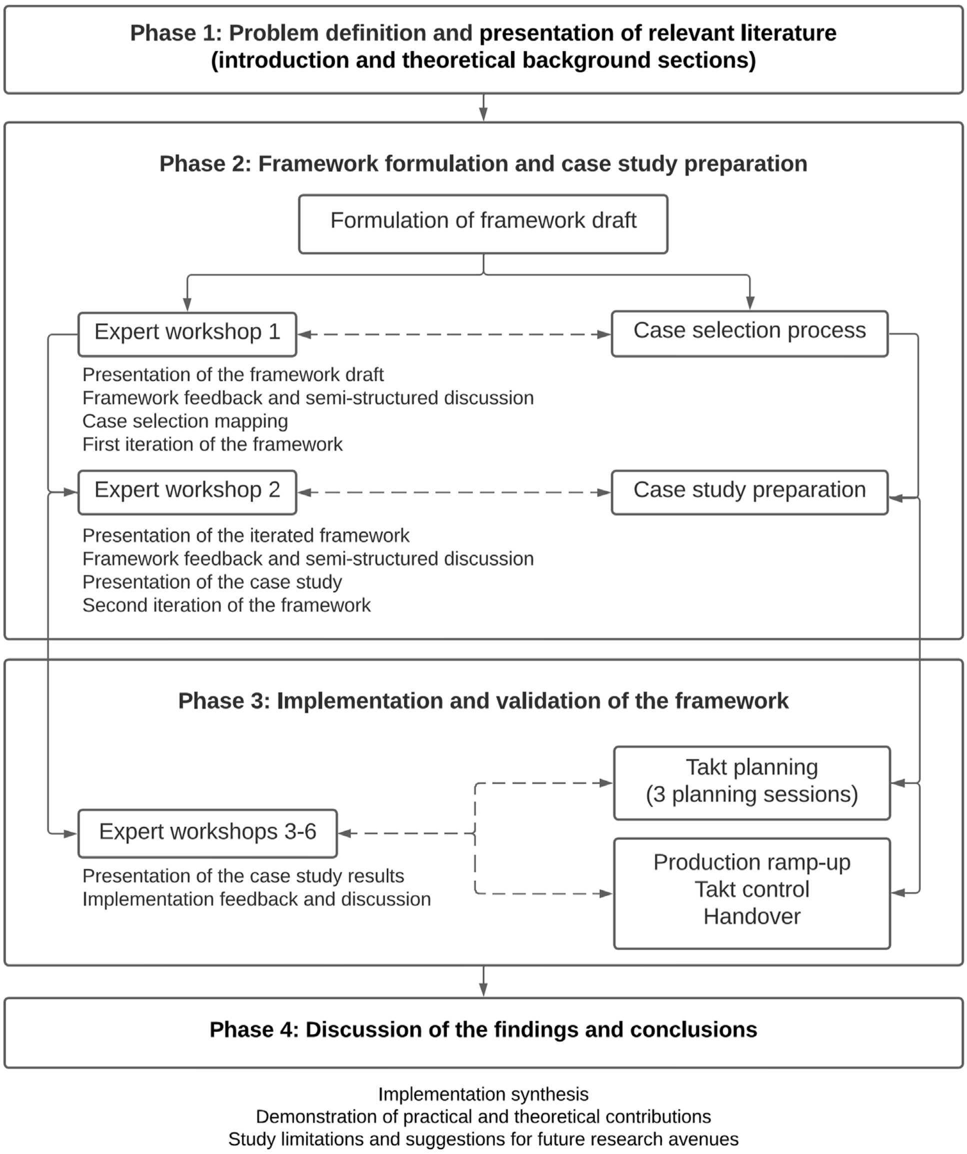

FIGURE 1
The flow of the study.

gathered using a web-based activation software in which the respondents answered the guiding questions during the session. Workshops 1 and 2 were conducted as live sessions, but due to the COVID-19 pandemic, the rest of the sessions were conducted virtually.

Case study

The possible case candidates were mapped during the first expert workshop, primarily looking to implement the framework in the represented companies' projects. The case was selected based on two criteria: willingness and ability to implement the framework; and access for data collection, including the possibility for site visits and interviews. The selected case was an industrial construction project in central Finland, where an existing manufacturing plant was extended with a new warehouse building, consisting of ~10,000 m^2 of space. The project's construction management company was eager to implement decentralized takt production to reach construction milestones, which were perceived as nearly impossible to achieve without a refined PP&C approach. The implementation targeted

TABLE 1 Summary of the case study data sources.

Data sources in the takt planning phase	3 planning workshops; researchers acted as facilitators. Takt planning data: schedules, meeting minutes, project diary, and workshop observations. 5 semi-structured interviews with crew leaders and workers *I1: Crew leader, sprinkler installation I2: Crew leader, electricity works I3: Worker, electricity works I4: Crew leader, general MEP works. I5: Worker, general MEP works*
Primary data sources in the takt control phase	5 semi-structured interviews with crew leaders and workers *I6: Worker, sprinkler installation I7: Crew leader, electricity works (same interviewee as in I2) I8: Worker, electricity works (same interviewee as in I3) I9: Crew leader, general MEP works I10: Worker, general MEP works. 7* semi-structured interviews with managers and a client representative *I11: Project manager, electricity works I12: Project manager, sprinkler installation I13: Project manager, general MEP works I14: Project manager, construction manager consultant I15: Project engineer, construction manager consultant I16: Site supervisor, construction manager consultant I17: Project manager, client*
Supporting data sources	Resource tracking data, schedule data, cost data, meeting minutes (including tracking of preconditions for/barriers to work), and a project diary written by a project manager. Observation: a site visit, and participation in two production meetings

the interior phase of the project, especially the mechanical, electrical, and plumbing (MEP) work, which were regarded as production bottlenecks. One of the authors (EL) was employed by the construction management company during the study, but did not have a role in the case project.

The sources of the collected data consisted of two primary and one supporting categories, respectively: 1) facilitation and observation of three takt planning sessions; 2) 17 semi-structured interviews with case participants; and 3) site observations, resource tracking data, schedule data, cost data, and production progress reports. The data sources are presented in Table 1. First, takt planning was conducted in three sessions in which the researchers acted as facilitators, guiding the process while training the project personnel to operate within the framework. Schedule and observation data were also collected during the takt planning phase.

Second, three rounds of 17 semi-structured interviews with a total of 15 interviewees (some of the interviewees were interviewed twice at different stages of the implementation) were conducted to obtain insights regarding the implementation. Semi-structured interviews were utilized to allow the participants to reflect on their experiences freely while guiding the conversation toward the RQ. The first and second interview rounds focused on the framework implementation from the site team's perspective, and the interviewees were trade crew leaders and workers. The third interview round focused on a managerial perspective, with the interviewees consisting of managers and a client representative. The first interview round was conducted on-site, but the second and third rounds were conducted virtually due to the COVID-19 pandemic. The interviews were recorded and transcribed, and the notes made during the interviews were also utilized in the analysis.

Third, production and observational data were collected to support the other data sources. The collected data included resource tracking data, schedule data, cost data, meeting minutes (including tracking of preconditions for/barriers to work), and a project diary written by a project manager (in which the site's progress was reflected daily from the construction manager's point of view). The data were obtained from general project documentation maintained by the construction management company. The observations were based on a site visit and participation in two production meetings. The COVID-19 pandemic restricted the possibilities for additional site visits and observation of site meetings. However, during the implementation, the authors were in close contact with the site personnel on a weekly basis, allowing data collection and observation of the site's progress remotely. In total, data collection lasted for 15 months (June 2019–August 2020).

Data analysis

The procedure for compiling and analyzing the data progressed through the development of the narrative, followed by data reduction and coding (Miles and Huberman, 1994). All the data were thematically coded and structured according to the inspected second-order (implementation steps, i.e., takt planning) and first-order themes (drivers/benefits/challenges, i.e., involvement of workers) and interpreted by looking for similarities, differences, and emerging themes among the responses and different data sources. Simultaneously, data that were not strictly related to the formulated themes were reduced to gain focus in the analysis and to reduce information that was not necessary to answer the RQ.

The workshop and the case data were partially analyzed and triangulated reciprocally during the implementation and validation phases, laying the ground for continuous discussion and feedback among the workshop experts, the case study participants, and the study authors. The main author was primarily responsible for analyzing and synthesizing the workshop and the case data, which helped align the discussion and the analysis among the authors. During analysis, illustrations and synthesis tables were also drawn from the results to guide the discussion and to provide a graphical representation of the results. Through iteration, these graphical representations formed the illustrations presented in the results section.

TABLE 2 Decentralized takt production framework.

Process step	Drivers for decentralization	Contribution to flow
1a Data collection and high-level takt planning		
Data collection: relevant production data are collected to form the basis for high-level takt planning. Data are gathered from building information models, productivity databases, and labor agreements and supported by the participants' personal experience. **High-level planning:** consists of defining goals and milestones based on the client's preferences, which allows determining initial values for the planning parameters (takt areas, takt time, takt wagons, buffers, and resourcing), further resulting in the first iteration of the production plan that sets boundaries for further, more detailed planning. It is conducted centrally by a "core" team, including, for example, the general contractors (GCs), project and site managers, the client, and possibly trade contractors' managers.	Centralized decision-making allows a meaningful overall balance between centralized and decentralized approaches and to effectively assess the overall flow and client's needs (Koskela et al., 2019, expert workshop feedback).	The focus is on initiating good overall flow, especially considering process flow conditions P1–P4 and P8 (Lehtovaara et al., 2021, expert workshop feedback).
1b Formulation of teams and decentralized takt planning		
Formulation of teams: the step begins by the core team forming wagon-based planning teams, which are based on the high-level plan and consist of trade crew leaders and workers that are part of the work activities within specific wagons. **Decentralized takt planning:** especially focuses on iterating the process within wagon teams by, for example, iterating task durations and sequence, buffers, and resourcing. The iterated decisions are reflected in the overall takt plan, while constraints and requirements for other wagons are communicated and solved in collaboration with the core team and other wagon teams. The teams should mutually agree on changes in mutual planning parameters (takt time, takt areas, wagon sequence task distribution, and buffers). The core team facilitates the process.	Ensures early, gradual, and intense involvement of teams; officially determining their responsibilities in decision-making; and allocating adequate time and resources for decision-making and problem-solving (e.g., Saurin et al., 2013, expert workshop feedback). It initiates trust and transparency amongst site teams and individuals (e.g., Chinowsky et al., 2010).	The focus is on improving operations flow (O1–O2) and ensuring that overall flow is maintained during the decentralized planning (initial discussions and expert workshop feedback).
2 Production ramp-up and takt control		
Production ramp-up: final coordination of takt control procedures is conducted to ensure a smooth start. Control mechanisms presented by Binninger et al. (2017) were adopted for takt control, which are also trained for all the participants before the production begins. **Takt control:** consists of short-cycled and visual production management through short progress meetings held every day by the core and site teams, accompanied by systematic quality control (including handoffs between every wagon where the quality defects are issued and preconditions for the next wagon are ensured). The decision-making authority to tackle more minor issues should be held within the decentralized teams, gradually involving other teams and the core team in the decision-making if necessary. The core team facilitates the process.	Empowers teams and individuals for autonomous decision-making in practice and ensures daily communication between site teams and management (e.g., Magpili and Pazos 2018, expert workshop feedback).	The focus is to especially ensure flow conditions P5–P7 and O1–O2 while maintaining good overall flow (Lehtovaara et al., 2021).

(Continued on following page)

TABLE 2 (*Continued*) Decentralized takt production framework.

Process step	Drivers for decentralization	Contribution to flow
3 Continuous improvement and training		
Continuous improvement (that aims to tackle emerging problems immediately) and training of the participants (especially trade crew leaders and workers, but also the core team members) should be ensured during the planning and control phases, and between projects.	To cope with the increased decision-making responsibility, individuals are trained and involved through the planning and control process (e.g., Saurin et al., 2013, expert workshop feedback).	Supports maintaining overall flow (Lehtovaara et al., 2021).

Results

Framework formulation and implementation process

The decentralized takt production framework was formulated based on the theoretical background and improved with feedback obtained from expert workshops 1 and 2. Table 2 describes the framework and how decentralization and production flow are considered in specific steps. Compared with other takt production approaches, such as takt time planning (TTP) (e.g., Frandson et al., 2013) and takt planning and takt control (TPTC) (e.g., Dlouhy et al., 2016), the presented framework has similarities with both; the overall process is aligned with the general implementation steps of takt production, which both TTP and TPTC utilize (Lehtovaara et al., 2021, see theoretical background). The most notable difference is that in the framework, the process is clearly split into centralized (high-level planning) and decentralized (decentralized planning, takt control, and continuous improvement) phases; in the decentralized phase, decision-making responsibility is partially distributed to the site teams and first-line workers, while the managers act as facilitators and ensure connectivity among the teams. TPTC is primarily driven in a centralized fashion, while in TTP, trade crew leaders' input is heavily used to aid in decision-making, initiating decentralization.[5] However, in TTP, the decision-making is still not extended to the worker level. Moreover, in contrast to TTP and TPTC, the proposed framework explicitly emphasizes the drivers of effective decentralization of decision-making, for example, by considering the site teams' needs in the decision-making process and providing them with adequate resources to succeed with their increased responsibilities.

In the inspected case, high-level takt planning was conducted through two planning sessions, and personal tasks (such as acquiring information and feedback) were assigned before and between the sessions to aid the planning process. In a third planning session, the formulation of wagon-based teams (composed of crew leaders and workers) and further iteration of the plan in a decentralized manner were conducted. As a result, the takt plan was divided into eight takt areas, consisted of 11 takt wagons, and proceeded with a 1-week takt time. In addition to the plan iteration, the takt control process was prepared in the third session. Takt control was planned to be coordinated through short daily site meetings, accompanied by longer weekly meetings in which the prerequisites for the subsequent week's work would be addressed. The participants were trained in using takt control mechanisms during the third planning session, which were also visualized in the site office. Because of the tight milestone dates demanded by the client, a soft start was not implemented, but it was agreed to pay increased attention to the production ramp-up.

Implementation findings

The implementation positively impacted project schedule performance, as illustrated in Figure 2. The original interior schedule was planned for 22 weeks, but due to a 6-week delay in the procurement process, the project team was pushed to seek improvement to reach the equipment installation start date required by the client. Takt planning resulted in a schedule of 17 weeks with interlaced handovers between construction and equipment installation, meeting the client's demands. The actual length of the interior phase ended up being 20 weeks (a duration reduction of 9%), but due to successful phase interlacing, the equipment installation was allowed to start at the desired date, resulting in a duration savings of 6 weeks or 23%. A project engineer stated that this would have been "impossible to achieve without the implemented framework" (I15). The positive effects on schedule performance were especially welcomed by the client (I17). For the client, meeting the specified milestone dates and visually understanding the schedule progress were seen as the most positive results of the implementation.

Challenges, primarily induced by external factors, caused a slight increase in the interior phase's length from the planned 17 weeks. The COVID-19 pandemic began during the production, resulting in quarantines, limited personnel access to the site, and material delivery problems. Additionally, a winter storm caused damage to an external wall, which slowed the work

5 While the TTP method descriptions do not present an explicit control approach, combining TTP with LPS has been proposed to provide an integrated approach for takt control and continuous improvement (Frandson et al., 2014).

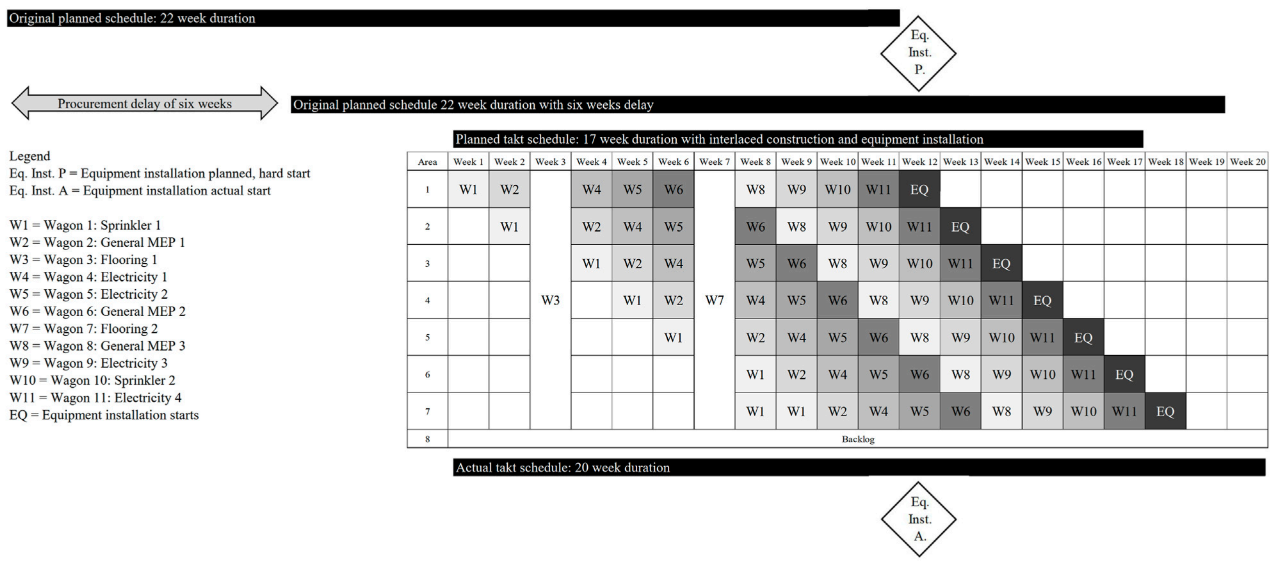

FIGURE 2
Implementation impact on project schedule performance.

in the interior phase for 2 weeks. Despite these challenges, the implementation achieved the desired schedule goals. The challenges required aggressive implementation of the control mechanisms and overtime work, causing a slight cost increase. However, this is not uncommon for first takt production implementation initiatives. Nevertheless, meeting the initial deadline was perceived as having more weight than the minor increase in construction costs.

Qualitative findings and sources of information regarding the implementation and expert workshop validation are presented in Table 3. In the takt planning phase, the framework implementation was perceived as yielding several benefits from both managers' and site teams' perspectives. The implementation process was seen to successfully employ decentralization drivers, such as increasing transparency and trust, which supported effective planning and utilization of site teams' knowledge and increased the plan's process and operations flow. In particular, the crew leaders' knowledge was regarded as beneficial in the process, particularly when coordinating the detailed work within and between wagons (interviewees I15, I16). These results were seen to contribute positively to worker well-being, collaboration within and between teams, and general production performance. The interviewees pointed out that the teams and team members had inherently good chemistry, which partially eased achieving these benefits. In contrast, slightly better worker involvement and more planning resources were suggested as primary development actions. However, providing even more resources for planning can also have adverse effects; acquiring site teams even earlier from their previous projects may not be possible due to resource constraints.

In the takt control phase, the weekly control meetings were experienced as highly beneficial and productive, leading the managers and crew leaders to collaborate effectively and implement swift adjustments when needed. Good site team dynamics created positive competition between the teams, urging them to keep the promised pace (I16). In contrast, one of the most prevalent drawbacks was the workers' seeming lack of participation in the decision-making process during takt control. The scheduled daily meetings were not held consistently, and takt control actions were mainly decided during weekly meetings that only the managers attended. The workers felt uninvolved, causing them stress. Several interviewees recognized this drawback (e.g., I6, I7, I8, I11, I13, I15) and pondered that deeper participation would have led to better collaboration and communication between individual members of collaborating teams. The lack of involvement also posed a barrier to thoroughly examining the effects of decentralization in the control phase.

The elements of good process flow were present quite clearly for most of the production duration, especially flow conditions P1–P3 and P8. However, a slight deterioration of process flow was observed in the beginning and ending stages of the implementation (specifically P4, P5, P7, and partially also O2). Regarding operations flow (O1–O2), the tracked resource needs of trade crews remained relatively stable and were mostly similar to or less than what was planned. With a highly predictable workload (I7, I13), the implementation resulted in good operations flow and a low amount of waiting time. For general MEP work, the resourcing was less than expected for most weeks; yet, the tasks were completed on time without a significant need for over-resourcing.

TABLE 3 Summary of the implementation results.

Implementation positive effects	Challenges and improvement suggestions
1a and 1b Takt planning	
The site teams' knowledge helped improve the plan's process and operations flows (*interviewees I4, I5, I11, I15, I16*).	Decentralized decision-making was partially dominated by the crew leaders; better involvement of workers is needed (*I2, I6, I16, planning session observation*).
The site teams were committed to the formed plan, and both crew leaders and workers (*I1, I2, I3, I4*) and managers (*I11, I12, I13*) had adequate resources and time for the preparation of work.	Decentralized planning requires the swift adaptation and absorption of information; even more time and resources for decentralized planning is needed (*I2, I11, I16*).
The planning process helped the team-building process, increasing transparency and trust between the site personnel (*I1, I2, I3*); a structured and detailed approach with timely involvement fostered effective and collaborative planning (*I13, I15, I16, I17, planning session observation, expert workshop feedback*).	The role of logistics planning should be increased in the planning phase (*I1, I2, I3, I11, expert workshop feedback*).
Tailored framework for the given situation supported implementation (*expert workshop feedback*).	—
2 Takt control and 3 Continuous improvement	
Effective collaboration, communication, and problem-solving between managers and crew leaders, especially through weekly meetings (*I4, I7, I13, I15*).	Lacking participation of workers in decision-making; more effort is needed on following the decentralized process promptly, ensuring the possibility for participation (*I6, I7, I8, I11, I13, I15, meeting minutes and meeting observation, expert workshop feedback*).
Adequate involvement and awareness were enabled by the intensive planning process, enabling swift adjustment of the plan when needed (*I11, I13, I13, I17*).	Inadequate involvement of workers caused stress for site teams (*I3, I4, I5, I6*); more resources for onboarding and training of workers were needed to ensure commitment (*I16, I17*).
Good site team social dynamics and positive competition between teams (*I16*).	The role of logistics control should also be increased in the control phase (*I12, I13, expert workshop feedback*).
Effects on flow	
Process flow: effective production planning, wagon handoffs, and a "ready with first-time attitude" helped achieve and maintain a good overall process flow; work was primarily in balance (process flow condition P1); the site teams respected the distribution of takt areas and takt times while primarily operating with the determined batch sizes (P2). This resulted in small WIP (P8) and small time buffers (P3), as tasks began after the preceding one ended (*I7, I15, project diary, meeting minutes*).	Process and operations flow: slight deterioration of flow at the beginning and end stages of the interior phase due to intensity of ramp-up (*I2, I16*), inadequately adjusted project phase interphases (*I4, I5, I6*), missing JIT logistics management (*I6, I7, I11*), and partial reliance on ad hoc management practices in the final weeks (*I11, I13*) resulted in a partially increased number of unnecessary activities (P4), re-entrant flow (P5), making-do (P7) and set-up times (O2).
Operations flow: primarily good operations flow (O1 and O2); low amount of waiting, stable resource needs (*I2, I3, meeting minutes, resource tracking*), predictable workload (*I7, I8, I11, I13*),	—

The general MEP works team observed that the tasks outside the interior phase (e.g., rainwater piping) resulted in slight resource fluctuation in the beginning, as the overlapping resource needs between the structural and interior phases were not considered in the takt plan (I4, I5). This highlights the importance of alignment between production phases, including those not part of the takt production implementation. In hindsight, general MEP team members recognized the alignment as a critical part of planning, especially as they had a large amount of work in other phases, affecting their task sequencing and resourcing. Simultaneously, an extended collaboration between teams operating in different production phases was seen as an improvement opportunity for better overall communication and collaboration (I5). For electricity, increased resources were needed in the end, but the electricity manager and the site team stated that the workload was still adequate and more predictable than usual, with an increased opportunity to affect their work sequencing (I7, I8, I11). The electricity team (I2, I3) reported that their operations flow was excellent compared with a traditional project as they could work independently in their reserved takt areas right from the start. Electricity team members were not accustomed to having space and time for their tasks, which are often scarce in traditional projects.

Discussion

Implementation synthesis

Overall, the results indicate that decentralized decision-making is suitable to be combined with takt production, resonating with previous findings of combining takt production with other decentralized approaches (e.g., Frandson et al., 2014). Observed from the case and the expert workshop results, the framework's implementation was primarily perceived as successful and yielding many lessons. In particular, the framework contributed positively to schedule performance (the implementation helped to achieve 23% duration savings in the interior phase) with interlaced construction and handover, with similar results to Dlouhy et al. (2017). Takt planning (where the participants' involvement was done granularly while transitioning from high-level to decentralized planning) was regarded as positively contributing to overall flow while advancing the drivers of decentralization, such as the site teams' increased commitment and decision-making power. Increased process flow after finding the production rhythm (Lehtovaara et al., 2021), the ability to solve emerging problems collaboratively and proactively (Frandson et al., 2014), and better control over production duration (Binninger et al., 2017) were also observed in the case at hand. Process transparency and increased plan reliability were documented as well, stemming from the benefits gained by previous decentralized PP&C implementations (Priven and Sacks 2015).

Takt control faced some implementation problems, while flow defects were experienced in the beginning and slightly at the end of production (similarly noted by, e.g., Lehtovaara et al., 2019). Similar to previously documented takt production cases, the increased role of logistics management, more intense involvement of trade crews in management practices, and increased efforts to ramp-up (e.g., Frandson et al., 2013), were also suggested as development actions in our case and expert workshops. These results appear to be quite usual for first-time takt production implementations (e.g., Lehtovaara et al., 2021), indicating that although the decentralized approach yields some unique benefits and concerns, all takt production approaches seem to have certain similar benefits to flow, especially process flow.

However, in contrast to other first-time takt implementation cases in which results for operations flow have often been ambiguous (e.g., Frandson et al., 2013; Alhava et al., 2019), the interview, meeting minute, and resource tracking data indicate that the operations flow conditions were perceived to improve in the case at hand. Adequate preparation in the planning stage and the teams' early involvement in decision-making (e.g., Chinowsky et al., 2010) built trust through the production (see also Humphrey et al., 2007; Yang and Guy, 2011), initiating healthy competition between site teams and helping them prepare for their work effectively. Adequate preparation and early involvement also eased the recognition of site teams' responsibilities during the (decentralized) planning (e.g., Bertelsen and Koskela, 2005) and in decision-making overall (e.g., Saurin et al., 2013), helping in obtaining the intended benefits and aiding in maintaining good operations flow during the production.

Improvement avenues for decentralizing decision-making in takt production

Despite these promising results, certain challenges and areas for improvement were also found for combining decentralized decision-making with takt production. Some of the drivers and expected benefits, especially those related to workers' personal performance, were not realized, partially due to inadequate implementation of the decentralized practices in the control phase. For example, although decentralized planning positively contributed to the site teams' commitment and motivation (Richardson et al., 2002), these elements were not observed during takt control as the decisions were primarily made at the managerial level. The control phase operated more in a centralized than a decentralized manner. The managers performed more as decision-makers than facilitators, while the teams were not empowered to act autonomously (contradicting decentralization drivers, e.g., Saurin et al., 2013; Magpili and Pazos, 2018). Lehtovaara et al. (2022) similarly observed that decentralized practices are often limited to the managerial and/or crew leader levels, which might result in inconsistencies between different decision-making levels and hamper the possibilities of improving management practices and overall flow. The expected drawbacks of decentralization, such as inconsistent coordination between teams (Stinchcombe and Heimer, 1985) and inconsistent knowledge sharing (Mintzberg, 1983), were surprisingly not caused by decentralized decision-making but rather due to the lack of it. However, it should be noted that these drawbacks were not largely present. The project's relatively small size and the initial transparency between its participants seemed to help overcome the disadvantages, which are especially prone to occur in large-scale and complex projects (Leavitt, 2005).

Although the external challenges (e.g., the COVID-19 pandemic that hampered the possibility for active framework implementation facilitation in the control phase) had a certain effect in terms of failing to extend the decentralization to the worker level in the control phase, it seems that successfully implementing all aspects of decentralization would nevertheless require a systematic effort over single projects (also Lehtovaara et al., 2022). Increasing the role of decentralized decision-making in the control phase would most likely require comprehensive cross-project and cross-organizational improvement and training of project participants to empower site teams with autonomy (e.g., Magpili and Pazos, 2018) and to train site managers to act better as facilitators (e.g., Saurin et al., 2013). With the existing management culture and practices, slipping into familiar, centralized production control is easy, even when decentralization would be viewed as a welcome change, as widely admitted by the study participants. These assumptions also resonate with a takt production maturity model (Lehtovaara et al., 2020), suggesting that succeeding in takt planning is relatively easy in the first implementation cases, but adopting the principles of takt control and adequate collaboration throughout the project often requires experience over several implementation attempts. It seems that the same progress toward higher maturity levels is present in decentralized takt production as well, further supporting the idea that takt production and decentralization share synergy advantages; however, further validation is needed to draw any definite conclusions. Also, the general experience of the teams should be considered when interpreting the results. Teams with greater experience, a background working with each other, and the ability and willingness to use innovative methods might possess a particular advantage in implementing novel approaches such as decentralized decision-making and takt production. In this case, although inexperienced with takt production, the site managers and teams felt generally positive toward the implementation, which should be considered when interpreting the results against future implementation cases.

Conclusion

Concluding notes and study contribution

In this study, we employed a design science research (DSR) approach to formulate, implement, and validate a PP&C framework that allowed us to evaluate the effect of decentralized takt production on production performance and flow. The studied framework considered the combined implementation of decentralized decision-making and takt production, including the viewpoints of site teams and first-line workers, which have been lacking in previous research initiatives. The results provide novel theoretical and practical contributions regarding both takt production and decentralized planning and control in the context of construction production flow management. Considering the RQ *How could combining takt production with decentralized decision-making affect construction PP&C practices and production flow?* We have observed that decentralization is suitable to be combined with takt production, aiding overall flow and schedule performance, even in a project where participants had no previous experience with takt production. Good operations flow was found to be especially supported by decentralized decision-making and the implemented decentralization drivers. These positive effects on flow were further supported by, e.g., observations on improved utilization of site teams' knowledge in planning, better commitment, communication, and team-building processes (further leading to increased transparency, trust, and problem-solving capacity), and positive competition between teams. The interior phase also achieved a 23% duration savings with interlaced construction and equipment installation, and stable resource utilization of trades. The decentralized decision-making practices were successfully implemented in the planning phase; however, the elements of decentralization were not adequately utilized in the control phase, resulting in the benefits not being obtained to their full potential magnitude.

For further implementation of decentralized takt production, the most critical improvement suggestions are as follows: 1) more systematic and cross-organizational involvement and training of decentralization principles should be ensured to empower site teams to act as autonomous decision-makers and managers to serve as facilitators; 2) more extensive training and implementation of takt production practices should be ensured for project participants, focusing on effective ramp-up and daily production control in which site teams (including workers) can actively participate; and 3) the role of logistics management should be improved, for example, by involving material suppliers and logistics operators in the decentralized PP&C processes. Notably, the suggestions for improvement are weighted toward training the participants and developing their understanding of takt production and decentralization practices. It seems that an extensive effort over single projects and organizations is needed to gain all intended benefits, while the competence to successfully operate with (decentralized) takt production increases with experience.

Study limitations and avenues for future research

Although the wide range of collected evidence offered a possibility to explore decentralized takt production in depth and increase the study's validity (Eisenhardt and Graebner, 2007), the setting of a single-case study has limitations for generalizability. Moreover, as the expert workshops were conducted with a pool of experts who were already interested in applying decentralized planning and control, confirmation bias toward the framework's benefits possibly exists, although the implementation challenges and adverse effects were also widely discussed. As the framework development was guided by iteration that considered the specific implementation situation, the utilization of the framework in different contexts should be supported by fitting the framework for the given setting. However, the perceived effects on flow could be considered rather universal, so they could be seen at least as a basis for evaluating the effects of decentralized takt production in other geographical locations, project types, or organizations.

Furthermore, the explorative findings were based on a combination of qualitative and quantitative data, which did not allow for assessing and comparing the quantity of flow effects unambiguously. Future research could validate the impact of decentralized takt production compared to other takt production and other PP&C approaches (such as LBMS) through a comparative, multi-case, quantitative analysis. However, one should bear in mind that even in multiple-case study settings, comparing the results might not provide unambiguous conclusions. The assessment of a schedule performance is always subject to the project's external and internal factors and the quality of the initial planning. Factors such as managers' and teams' experience, management style, and leadership attributes can affect how decentralized decision-making and takt production implementation can succeed. Moreover, longitudinal effects of the approach, particularly in cases with higher takt production maturity, could be considered as future research initiatives. It could also be explored how spatiotemporal planning, providing a computer-aided and automated approach, would affect decentralized takt production performance. Finally, in future research, a framework calibrated more explicitly toward pure decentralization could be interesting to implement; however, to succeed, it might need the aforementioned high maturity and/or remarkably increased effort and capacity to drive the process toward pure decentralization of PP&C.

Data availability statement

The datasets presented in this article are not readily available due to privacy restrictions. Requests to access the datasets should be directed to JL at joonas.lehtovaara@aalto.fi.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements.

Author contributions

JL conducted the study design with the assistance of OS. JL and EL conducted the data collection and analysis. JL conducted the literature review, prepared the first draft of the manuscript, and finalized the manuscript. All authors (JL, EL, OS, AP, and PU) participated in revising and editing. All authors have read and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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