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Analyzing the benefits of RFID technology for cost sharing in construction supply chains: A case study on prefabricated precast components

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ABSTRACT

The problems encountered in the current manual material tracking methods result in late deliveries, missing components and incorrect installations. Automated data collection technologies, such as Radio Frequency Identification (RFID), are promising technologies that can be used to efficiently track components in construction supply chains. However, it is still not clear how the cost of technology investment should be shared among supply chain members. This study proposes the use of a cost sharing ratio, which is calculated for each party based on the benefits received. A case study was conducted at a prefabricated exterior concrete wall panel supply chain, and a simulation-based decision-support tool was used to model the current manual phase and automated phases. The simulation results were used to determine and analyze the benefits and related cost savings of RFID for each party, and a cost sharing ratio was calculated for distributing the technology investment cost among parties.

1. Introduction

It is a challenging task to efficiently identify, track and locate components through a construction supply chain as it is usually performed manually by using paper-based methods. The problems encountered in the current manual material tracking methods result in late deliveries, missing components and incorrect installations, which lead to additional labor and material costs. Previous studies show that automated data collection technologies (ADCTs) (i.e., radio frequency identification (RFID), laser scanner, global positioning systems (GPS), wireless sensors, high-resolution cameras, ultra wideband) can be used to improve the efficiency of identification and track activities in the construction industry [1–9]. However, it is still difficult for construction practitioners to make an investment decision since it is not clear how the cost of an ADCT investment will be shared among different parties.

The study explained in this paper proposes to calculate a cost sharing ratio for distributing the cost of ADCT in a construction supply chain based on the benefits received by each supply chain member. Some previous studies identified the benefits of ADCT by focusing on certain tasks and quantifying the benefits of ADCT for performing specific activities, such as identification, locating, delivery and receipt of construction components [2,6,10,11]. In other studies, the advantages of ADCT were determined through simulation models by comparing current processes with automated processes [1,12,13]. In these studies, the identified benefits of ADCT for the construction industry were limited to certain activities, which are usually observed in one phase.

This paper presents a case study and a simulation-based decision-support tool which was developed: (1) to assess the benefits of ADCT utilization for different parties in a supply chain; and (2) to identify how the investment cost will be distributed among these parties. In the case study, a supply chain of prefabricated concrete wall panels was investigated. Simulation models were developed to quantify the benefits of each party for the base case and ADCT cases. Basic production, transfer and installation activities were modeled focusing on operational activities, such as related identification and locating tasks in the prefabrication and the construction phases. The analysis of the simulation results shows the benefits (i.e., time savings) observed by using two ADCT based approaches (e.g., semi-automated RFID and automated RFID). Related cost savings were determined and a cost sharing ratio was calculated for the supply chain members based on the cost savings of each member.

2. Background research

In the current material tracking approach, paper based methods are used when transferring, locating, shipping and receiving prefabricated concrete wall panels in construction supply chains. Previous research studies highlight that the manual material tracking approach is time consuming and results in late deliveries, mislocated

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components and incorrect installations [2,4]. To improve the current process, the utilization of ADCT for material tracking was proposed and the technical feasibility of using these technologies in construction supply chains were validated [2–4,6,14]. For example, Jaselskis and Misalami [2] showed that RFID technology can be utilized while receiving pipe hangers, and Goodrum et al. [3] proved that RFID technology can be used for tool tracking at a construction site. Another research study conducted by Bohn and Teizer [6] examined the use of digital cameras to monitor management related tasks, such as tracking and updating project schedules.

To utilize a technology in supply chains, technical feasibility is not the only criterion that should be met. There is also a need to identify how the cost of technology investment will be distributed among different parties. Similar studies were performed in other domains, such as the retail industry [15–17]. For example, Ustundag [17] identified the benefits of using RFID technology in the textile industry, and calculated a cost sharing factor for the different parties of the supply chain (i.e., retailer, distributor and manufacturer). A similar approach was followed in the study explained in this paper.

In previous studies on determining the benefits of ADCT in the construction industry, most of the field tests that were performed focused on the benefits of a technology for a specific activity or a phase (e.g., receiving activity or the construction phase) [2,6,10,11,18,19]. For example, Grau et al. [11] identified an 87.5% time savings in locating steel components through automation in tests conducted on activities performed at the construction site (i.e., the laydown yard and the installation area). Yin et al. [14] used RFID to locate precast components at a plant, and found that the duration of the locating process decreased from 25.23 min to 0.57 min. In another study, Jaselskis and Misalami [2] utilized RFID in receiving pipe hangers, and the results showed a 30% time savings during the receipt of 100 hangers. Bohn and Teizer [6] presented the benefits associated with the use of high-resolution cameras at a construction site for monitoring tasks, such as resource management, safety management and management of travel between the project site and the main office by executives. The yearly savings for the construction site was estimated at $405.50 for avoiding external communication, and $491 for avoiding each unnecessary worker in each related task [6]. Additionally, Nasir et al. conducted a cost–benefit analysis of an automated construction materials tracking system that located materials (e.g., pipe spools and valves) via RFID and GPS at the job site. The findings show that the crew size reduced from eighteen to twelve (i.e., a 33% labor savings) due to automation [18]. In another field test, the impact of wireless systems was investigated. The technology selected was wireless cameras, which were deployed at a construction site for monitoring the work progress (e.g., the erection of structural elements) and the conditions at the jobsite [19]. The cost–benefit analysis reported an overall saving of approximately $18,000.

In other studies simulation models were used as decision making tools to assess the impact of technology use in different phases of the construction supply chains instead of field tests [1,12,13,20]. For example, a simulation model was developed to identify the effects of an ADCT (i.e., bar coding) on increasing the efficiency of asset management in the maintenance phase [1]. In another study, the process of productivity data collection from the construction site was simulated for RFID and laser scanner technologies [12]. Jang and Skibniewski also developed a simulation model to perform a cost–benefit analysis for comparing manual and sensor-based methods (i.e., RFID and wireless sensors). Labor hour savings associated with material and information handling tasks were determined, such as check-in and installation of steel structural elements performed in the construction phase [20]. This study found that RFID-based tracking methods resulted in up to 35% in savings [20]. Finally, Young et al. [13] presented the initial results of a simulation model developed for a supply chain to reflect the impact of automated materials tracking technology on the visibility of materials. These studies mostly focus on one activity or phase when determining the benefits. On the other hand, the study presented in this paper considers the entire supply chain when identifying the benefits of ADCT to determine a cost sharing ratio for different parties.

3. Case study and data collection

This paper investigates a supply chain of prefabricated concrete exterior wall panels. Fig. 1 presents an overview of the production area in the plant. The dimensions of a prefabricated panel are 3 m by 5 m (Fig. 1). 3500 pieces of prefabricated concrete panels were produced for the investigated project: a 126,000 m^2 residential building project. At the production plant, it takes 24 h to produce a panel; therefore, they operate in multiple-shifts. At one time, approximately 500 pieces of panel are kept in the storage area at the plant while 70 panels are stored in a laydown area at the construction site. The storage area and laydown area, which are both outdoors, are divided into grids with unique IDs, and each grid is approximately 8 m by 12 m. The grid ID is used to record the storage location of each panel. The construction site is an hour away from the plant, and each truck used in transportation can hold 9 panels.

The case study modeled the operational activities (e.g., identification and locating), which are performed during the production, storage and installation of the panels in the prefabrication and the construction phases. Data for the case study was collected by interviewing seven practitioners from the precast and construction companies. Moreover, observations were made at the plant and at the construction site. During data collection, activities in the supply chain were monitored with a focus on identification, locating, and storage activities, and the duration of each activity was determined. Also, probabilities of occurance were identified for some of the activities, for example, for activities that are performed in case of a problem.

Based on the information collected from the case study, the current process for the base case was defined, and a simulation model was developed. RFID technology, which is a type of ADCT, was selected. Processes describing two different approaches for the application of RFID were modeled: (1) to determine the benefits (e.g., time savings) of an ADCT by comparing RFID cases with the base case; and (2) to compare the benefits of a fully-automated approach with a semi-automated approach. For the identified benefits, related cost savings were determined and a cost sharing ratio was calculated for the supply chain members based on the cost savings of each member.

3.1. Current process (base case)

The investigated supply chain includes the fabrication and handling activities of wall panels at a production plant, the shipping activities, and the handling and installation activities at the construction site. An overview of the current process is given in Fig. 2. In the current practice, after a panel is produced (Fig. 2, step 1), workers tag the panel with a paper-based label, which is used to track and locate panels throughout the supply chain (Fig. 2, step 2). In the plant and at the construction site, the panels are stored based on their destination and delivery date; thus, this information is included on the labels along with the panel ID, and used when moving panels to the storage area.

Once the panels are produced and labelled, they are transferred to the storage area in the plant (Fig. 2, step 3). Transferring panels to the storage area includes some subtasks, which are also modeled in the simulation. These include, for example, selecting a grid in the storage area, loading panels onto a forklift and transferring panels to the storage area. When recording the location information of the panels in the storage area and in the laydown yard, the panel's ID and grid ID are used.

After a list of panels to be shipped to the construction site is received from the site, the panels are located in the plant's storage area (Fig. 2, step 4). The location of the panel (i.e., grid ID) is retrieved from the records in the layout plan, and a worker looks for the panel.

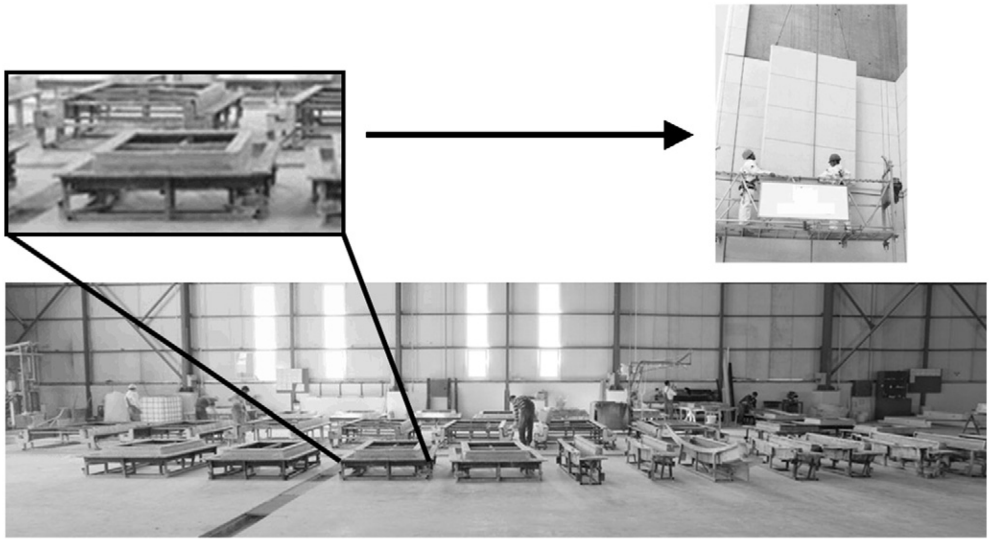

Fig. 1. Prefabricated panel production area and installation of panels at site.

If the worker cannot locate the relevant panel, an extended search is conducted in the plant (Fig. 2, step 5). In the extended search, two workers look for the panel in the entire storage area for a longer time (i.e., from a minimum of 30 min to a maximum of 120 min). Unless the panel is found after an extended search, the panel has to be produced again. Otherwise, the workers load the located panels onto a forklift to place them on a truck for shipping to the construction site (Fig. 2, step 6).

When receiving panels at the construction site, workers check the panel IDs (Fig. 2, step 7). If any missing panel exists, the manufacturer is notified to initiate an extended search in the plant (Fig. 2, step 5). The panels that are received at the construction site are transferred to the laydown area (Fig. 2, step 8). A mobile crane is used to unload the truck, and a forklift is used to carry the panels to the laydown area. The location of the panel in the laydown area is recorded by a worker on a layout plan.

Before installation, the panel is located in the laydown yard (Fig. 2, step 9), and a mobile crane carries the panel to the installation area (Fig. 2, step 11). It is reported that in some cases, incorrectly identified and shipped panels cannot be detected until they are being installed. In this case, the panel is lowered down and taken back to the storage area. Consequently, an extended search is carried out at the construction site to locate the missing component (Fig. 2, step 10). If the required panel cannot be found at site, another extended search is conducted at the plant. When the panel cannot be found either at the construction site or at the plant, it needs to be produced again.

The manual approach contains the following inefficiencies: (1) a time-consuming identification and locating processes, such as the additional time spent in finding missing components (i.e., extended search by two workers), (2) the remanufacturing of missing components, and (3) the transfer of remanufactured components to site. These inefficiencies result in additional material, labor, equipment and shipping costs. By integrating ADCT into the current manual approach, the number of missing panels after an initial search would decrease due to its high accuracy in the identification of components. Therefore, less time would be spent performing extended searches. Also, fewer panels would be remanufactured, and the identification and locating processes would be more efficient. The cases in which RFID are used for the same process are explained in the following section.

3.2. RFID cases

To improve the inefficiencies encountered in the manual process, it is envisioned that active RFID technology will be used for identifying and locating panels. The tags that are attached to the panels will be used to automatically identify the components throughout the supply chain. RFID technology that is integrated with GPS will be used to locate components. Two scenarios were developed to compare the benefits of the RFID-based process: (1) a semi-automated (SA) process and (2) a fully-automated (FA) process. In the SA process, the RFID tags that are attached to the panels are individually scanned by the workers who carry handheld readers. A similar experimental setup was used in Grau et al. [11], and the technical feasibility of such a system was validated through site experiments. On the other hand, in the FA process, human intervention is minimized and the tagged items are scanned automatically by the readers installed at forklifts or at the gateways. A similar system was tested under real-life conditions in Song et al. [4].

The proposed RFID-based processes extend the current process, which is shown in Fig. 2. The RFID-based processes include the same basic production, shipping and installation activities. However, the manual identification and locating activities given in the current process were replaced by semi-automated or automated activities.

In the RFID-based process, RFID tags that contain the ID, delivery location and date related to the panels are attached to each panel after its production (Fig. 2, step 1 and 2). Destination and delivery time information are stored on the tags to save time and minimize errors in the storage area and the laydown yard. In the SA approach, similar to the base case, a grid-based approach is used when storing panels at the plant, and each grid has an RFID tag that stores a unique ID. In the SA case, after a panel is transferred to the storage area at the plant, a worker carrying an RFID reader scans the panel's ID and grid's ID from the related tags and transfers this information to a database (Fig. 2, step 3). In the FA case, a GPS and a weight sensor are installed at the forklift to automate the process. Instead of grid's ID, the coordinates of the panels are automatically retrieved from the GPS. The ID of the panel is detected by the reader that is installed at the forklift. The weight sensor on the forklift (1) activates the RFID reader, which scans the panel's tag as the panel is loaded on the forklift, and (2) activates the GPS receiver which sends the coordinates of the panel when it is unloaded.

To locate a panel for shipping, a worker retrieves the location ID of the panel (i.e., grid ID for the SA case and coordinates for the FA case) from the database. In the SA case, the worker scans each panel in the identified grid on an RFID reader at the storage yard to locate the required panel. In the FA case, the operator of the forklift locates the panel based on the retrieved coordinates (Fig. 2, step 4). Moreover, similar to the base case, if there are any missing panels at the plant,

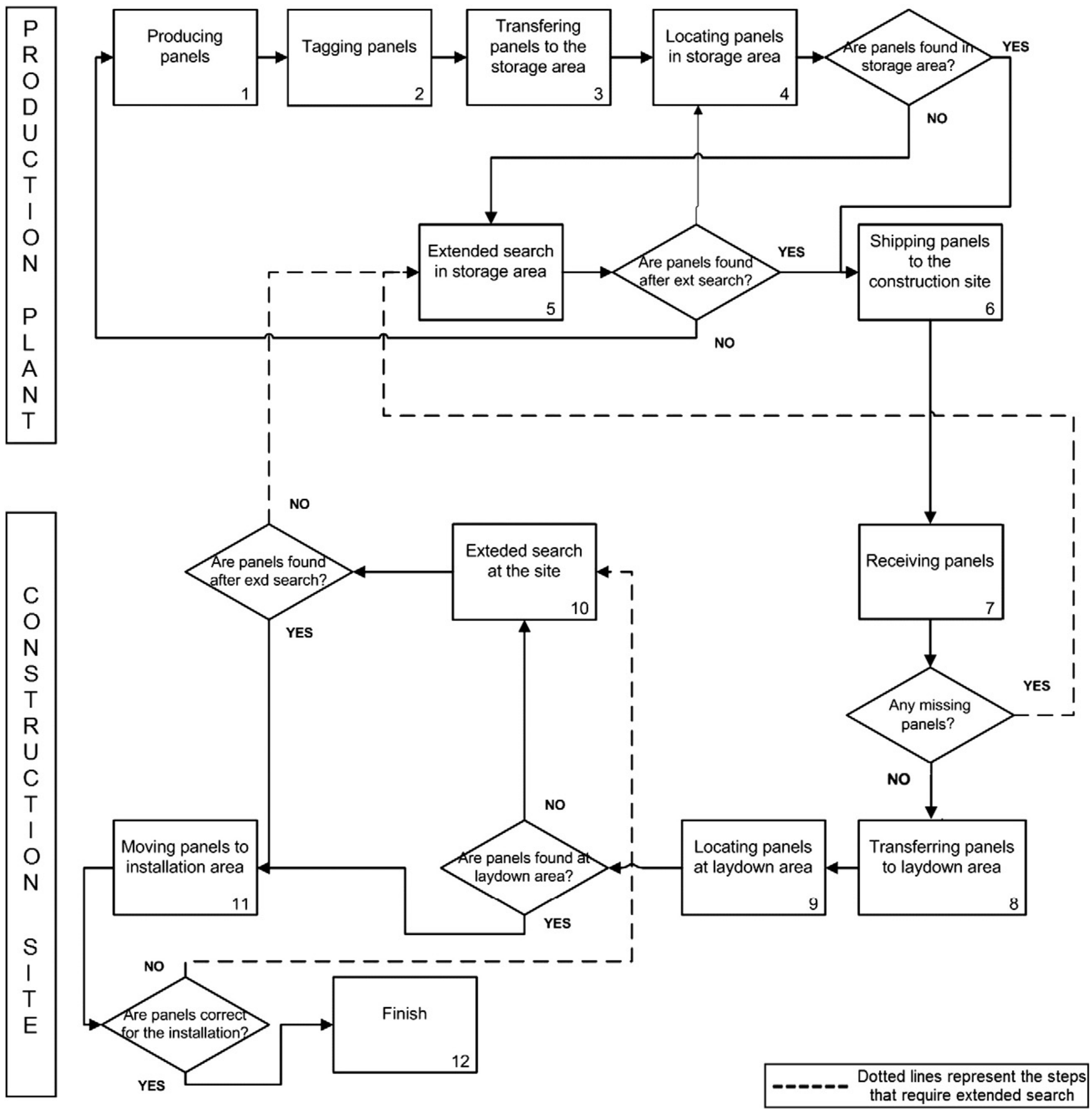

Fig. 2. Process for the base case.

an extended search is performed. The SA and FA approaches use the same methods for storing and locating components in the laydown yard at the construction site (Fig. 2, step 5).

During receiving of the shipped panels at the construction site, a worker scans all the panels individually to identify the panels in the SA case. Whereas in the FA case, the panels are automatically scanned by the readers placed at the gate as the truck that carries the panels enters the site (Fig. 2, step 7). The IDs of the scanned panels are sent to a database and the list of requested panels is checked against the list of received panels. If any missing panel is identified, an official report is automatically sent to the plant.

Panels are transferred to the laydown yard and located at the construction site by following the same approaches used in the plant (Fig. 2, step 8 and 9). If the required panels cannot be identified at the construction site during locating process, an extended search is performed in the same way as it was performed in the plant (Fig. 2, step 10).

Similar to the base case, if the panel cannot be installed properly, it is identified that the panel is not the correct one. Thus, it is lowered down and transferred back to the storage yard by a forklift. In this case, an extended search is performed at site and at the plant if needed.

4. Simulation models

In this research study, three different simulation models were developed: one for the base case and two for the SA and FA RFID cases. The goal was to determine the benefits of using RFID technology and also to compare the benefits for the SA and FA cases. A discrete event simulation approach was followed to represent activities performed across the supply chain of prefabricated wall panels. A discrete event simulation technique was selected since it has been accepted as an appropriate method for the quantitative analysis of operations and processes performed in the construction industry [21]. The simulations were created

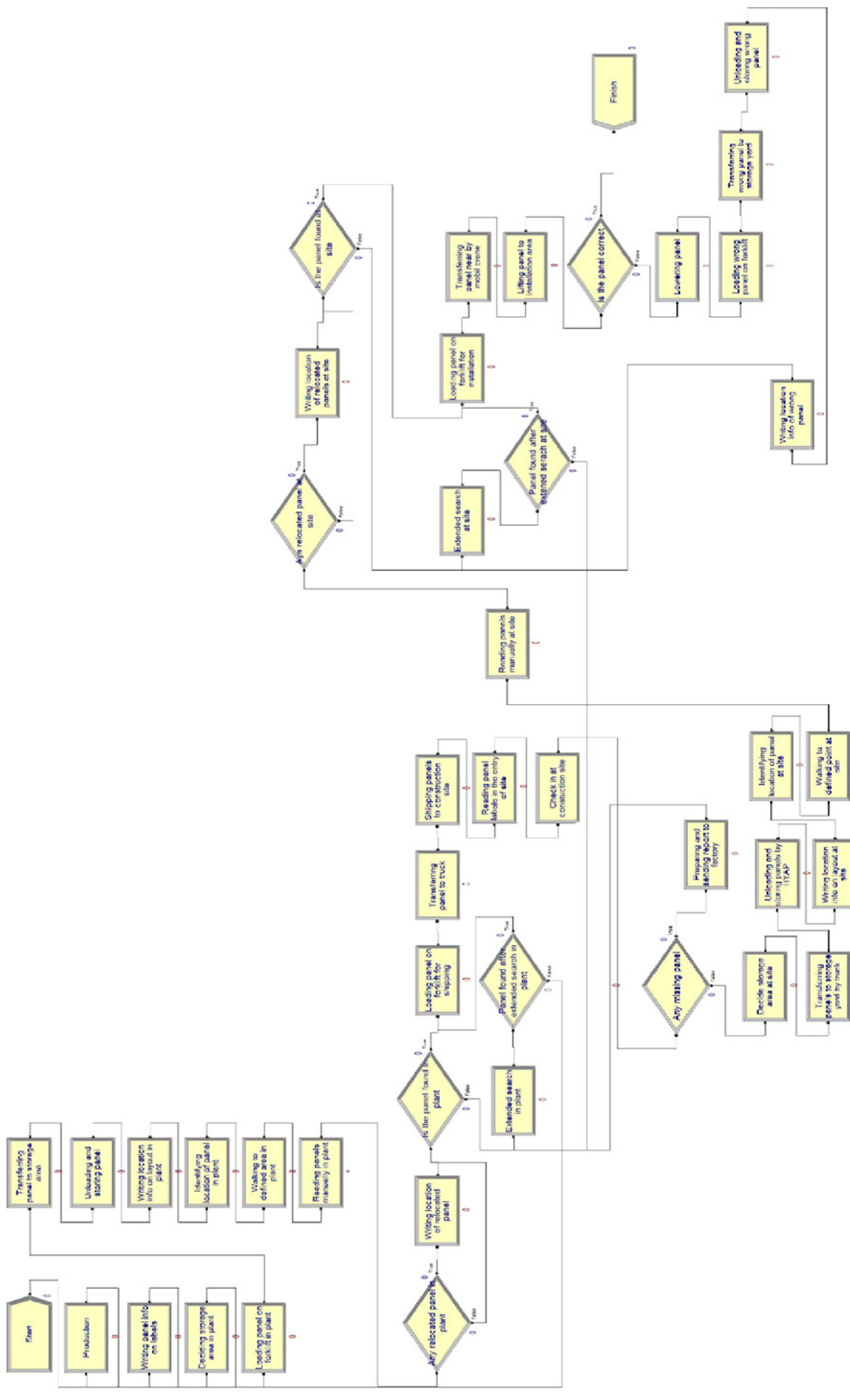

Fig. 3. The simulation model for the base case.

Table 1
Minimum and maximum durations of the related activities for each case (minutes).

Activity	Base case		SA RFID		FA RFID	
	Min	Max	Min	Max	Min	Max
Writing to RFID tags/labels	0.25	0.75	0.9	1.1	0.9	1.1
Selecting storage area in plant	1.2	8	0	0	0	0
Recording panel location in plant	0.2	1.33	0.45	0.55	0.18	0.22
Identifying panel location in plant	2.5	15	0.18	2.2	0.18	0.22
Scanning/reading panels in plant	1	6	0.51	0.63	0.51	0.63
Sending/writing relocated panel location in plant	0.4	2.67	0.45	5.5	0.18	0.22
Scanning/reading panels at the site entrance	0.63	2.5	0.51	0.63	0	0
Checking in at construction site	0.5	2	0.18	2.2	0.18	2.2
Creating report for missing panels	2.5	10	0	0	0	0
Selecting lay down yard at site	6	18	0	0	0	0
Recording panel location at lay down area	0.4	1.2	0.45	0.55	0.18	0.22
Identifying panel location at lay down area	1.5	7.5	0.18	0.22	0.18	0.22
Scanning/reading panels at site	0.6	3	0.51	0.63	0.51	0.63
Sending/writing relocated panel location at site	0.4	2.67	0.45	0.45	0.18	0.22

by using the academic version of the Arena simulation software package (v.11 — CPR 7).

The supply chain that was investigated is a two-echelon supply chain (i.e., production plant and construction site). In the simulations, the uncertainties in activity durations and the probabilities of occurrence for some activities were modeled for the prefabrication and the construction phases. The activities that were included in the models are related to the production, installation, and management of the storage, delivery and installation activities at the plant and at the construction site. The models were based on the process given in Fig. 2; however, they are more detailed than the process presented in Fig. 2 since some of the steps in the process are divided into sub-activities. Fig. 3 presents the simulation model developed for the base case.

The input values (i.e., duration and probabilities) for the base case were retrieved from the interviews that were conducted with four engineers from the production plant and three site engineers from the construction site. In addition, observations were made at the plant and at the construction site. For the base case activities, practitioners that were interviewed provided a uniform range for the durations of each activity (i.e., minimum and maximum durations). Thus, uniform distribution was used for the inputs of the base case. The probability values were also provided by the practitioners.

Since RFID technology was not being used in the observed plant and construction site, the durations and probabilities of occurrence for the SA and FA RFID cases were adapted from the previous RFID field studies [2,11,14] by integrating the observations made at site. Previous RFID field studies that have similar characteristics with the SA and FA RFID cases [2,11,14] were selected to determine the duration of the activities. While the values of similar activities have been taken from previous studies without any modification; some have been adapted to the investigated case according to the conditions of the production plant and the construction site observed during site visits. For example, the durations of the activities performed at the production plant are taken from [14], in which precast concrete components (e.g., walls, beams) were identified and related information was tracked via RFID in a production plant. On the other hand, the duration of activities that are related to locating the panels at storage or lay down yards through RFID and GPS, are adapted from [11] using observations made at the site, as the site conditions and technology used in this study are similar to those of SA and FA RFID cases. In [11], the location of steel components was tracked at the jobsite through material handling and installation processes at site via RFID and GPS. Finally, for the activities related to the receipt of materials, the durations are calculated based on [2], in which the material receipt of pipe supports and hangers were performed via RFID. In the previous studies, only the average durations of RFID related activities were provided. In this study, to include potential variations in durations, uniform distribution is used and minimum and maximum values for the uniform distribution is included. It is assumed that the minimum duration is 10% less and the maximum duration is 10% more than the average duration. Table 1 reports the activities that have different durations for the base case and RFID cases (e.g., identifying panel location in plant). While determining the probabilities for the RFID cases, previously mentioned RFID studies in the literature were examined [2,11,14] to determine the success rate of RFID technology. The probabilities for the RFID cases were then adapted to the investigated case by integrating the observations made at site.

All three models were created for the supply chain of 150 prefabricated precast components, which take five months to produce. The total time needed to produce 150 panels was calculated at 3600 h (150 panels × 24 h), which is the replication length (i.e., total simulation time) of the simulation. Each simulation model was simulated 1000 times.

As seen from Table 1, all the durations related to the identification, handling and locating of the panels decreases for the RFID cases when compared with the related durations in the base case, except the "writing to RFID tags" activity. Entering panel information on RFID tags takes more time than the writing process in the base case because it takes less time to write a piece of information on a label in handwriting compared with entering the same information via an RFID reader. The duration for the "selecting storage area" activity both in the plant and at the construction site is negligible when RFID technology is used. The reason is that in the RFID-based systems, the site layout plan which includes the panel's storage locations are digitally available to the workers at site. Also, since this information is collected digitally, its accuracy is high. The workers can immediately select the storage area based on this plan; therefore, in the RFID cases, no additional time is spent for searching for the correct storage location for each panel. However, in the base case, although the panel location information is also shown on a paper-based layout plan, the delivery dates in each grid are checked manually to ensure that the information in the layout plan is correct, as sometimes there are mistakes in manually recorded data.

When storing panels at the plant and at the site, a grid-based location identification approach is followed in the SA RFID case, and GPS-based locating is applied in FA RFID case. For the SA RFID case, the grid's location ID and panel's ID are scanned individually by a worker. Therefore, it takes longer to record a panel's location compared with the related duration in the FA case, in which location information is retrieved by GPS.

"Receiving at site" was represented by three activities in the simulation; scanning/reading panels, checking in and sending reports. In the base case, the panel's tag is located and read by a worker (i.e., from a minimum of 0.63 min to a maximum of 2.5 min). In the SA RFID case, the duration of scanning/reading activity is less as the panels are individually scanned by a worker (i.e., from a minimum of 0.51 min to a maximum of 0.63 min). In the FA RFID case, the panels are automatically scanned as the truck carrying the panels enters the site; thus, no duration is assigned to this activity. During "checking in", the list of shipped panels is checked against the required panel list. This activity takes a minute in the base case since

Table 2
Minimum and maximum durations of the activities that have the same durations for each case (in minutes).

Activity	Base case	
	Min	Max
Extended search at plant	30	120
Shipping panels to site	50	60
Extended search at site	20	80

Table 3
Probabilities for the base case and RFID cases.

Percentages	Base case (%)	RFID cases (%)
Relocated panels in the plant	50.0	50.0
Panels located in plant (initial search)	65.0	99.5
Panels found after extended search in plant	97.0	99.5
Missing materials identified during receiving	5.0	0.05
Relocated panels at construction site	50.0	50.0
Panels located at construction site (initial search)	80.0	99.5
Panels found after extended search at site	99.0	99.5
Correctly identified pieces for installation	97.0	99.5

the arrived panels list is compared manually with the required panel list. The same process takes 0.2 min on average (i.e., from a minimum of 0.18 min to a maximum of 0.22 min) for the RFID case as the arrived panels list is sent from the RFID reader to a database where it is automatically compared with the required panel. Finally if any missing panel is identified at site, an official site report is prepared and sent via the Internet. In both of the RFID cases, this report is prepared automatically; therefore the "creating report for missing panels" activity has negligible duration in the RFID cases.

Table 2 shows the activities that have the same duration values for each case. The durations of these activities are not directly affected by the technology utilization; however, the probability of occurrence for these activities changes due to technology use. Table 3 presents the probabilities of occurrence for the activities in the base case and in the RFID cases. While the probabilities of the base case activities were provided by the practitioners during interviews; probabilities for the RFID case activities were obtained from previous RFID studies. The probabilities related to inefficiencies (i.e., the percentage of missing panels) decreases in the RFID cases. For example, the percentage of located panels during the initial search at the storage yard in the plant increases from 65% to 99.5% when RFID is utilized, and the percentage of missing materials identified during receiving decreases from 5% to 0.05%.

4.1. Simulation results

The simulation results demonstrate that the use of RFID technology eliminated incorrect shipments and missing panels. Table 4 presents the total number of incorrectly shipped/identified panels and missing panels among the 150 panels that were produced in the base case and RFID cases. Incorrectly shipped panels are panels that are sent to the site without being requested, and incorrectly identified panels are panels that are not the right panels needed for installation. Incorrectly shipped or identified panels result in late deliveries and additional transportation costs. On the other hand, missing panels must be remanufactured, leading to additional production costs. According to the results, eight panels were incorrectly shipped to the site and five panels were incorrectly identified during installation in the base case. Also, two panels went missing at the plant and one panel went missing at the site. RFID technology, completely eliminated the problem of incorrectly shipped/panels and missing panels (i.e., zero incorrectly shipped/panels and missing panels at the plant and at site). This reduction also decreased the accumulated duration of some activities as these activities were performed fewer times (i.e., extended searches).

Table 4
Number of incorrectly shipped and missing panels in plant and at construction site.

	# of incorrectly shipped or identified pieces		# of missing panels	
	Base case	RFID cases	Base case	RFID cases
Plant	8	0	2	0
Construction site	5	0	1	0

Accumulated durations of activities represent the total amount of time spent for the given activity for 150 prefabricated concrete panels in the supply chain. The simulation results highlight an important reduction in the accumulated duration of some activities (Table 5). The activities that are included in this table have different accumulated durations for the base case and the RFID cases. Other activities such as loading to forklift or shipping panels to the construction site are not included in this table, because utilization of RFID technology does not change the accumulated durations of these activities.

All the related activity durations in the RFID-based cases decreased except the labeling activity. This was expected since the duration of this task (i.e., input parameter of the simulation) was also longer for the RFID cases. Two of the most significant reductions in the accumulated durations were observed in the extended search durations, both in the plant and at the construction site. By using RFID technology, the extended search durations decreased by up to 99% in the plant (i.e., from 75.78 h to 1.05 h) and by 96% at the construction site (i.e., from 28.69 h to 1.25 h). This reduction is due to the decreased percentage of missing panels that need to be found by extended search for RFID cases. When most of the panels are located in the initial search and do not go through extended search, the accumulated duration of extended searches decreases.

Another significant decrease was observed in the selection of storage area both in the plant and at the construction site. The duration of this activity is negligible for the RFID cases as explained in the previous section; therefore, 11.57 h in the plant and 29.86 h at the construction site were saved in total.

In the investigated supply chain, when the operational activities that have varying durations for the base and RFID cases are considered, significant time savings were identified for the SA and FA cases. For the specified activities, 209.54 h were spent in the current manual approach while 14.28 h were spent in the SA RFID case and 10.62 h spent in the FA RFID case. This indicates that approximately 195.4 h (i.e., 93%) were saved by integrating SA RFID technology with the current manual approach, whereas approximately 199.1 h (i.e., 95%) were saved by using FA RFID technology. When all the activities included in the simulation are considered (i.e., all activities related to the production, handling and installation of the panels), the savings accounts for an approximate 5% total time savings. Since some activities, such as production, have longer durations (i.e., 24 h), time savings is less for all activities than for the specified operational activities.

Table 5
Accumulated activity durations (in hours).

Activity	Accum. base case	Accum. SA RFID	Accum. FA RFID
Writing RFID tags/labels	1.26	2.48	2.48
Selecting storage area in plant	11.57	0	0
Sending/writing panel location in plant	1.93	1.24	0.50
Identifying panel location in plant	22.00	0.50	0.50
Scanning/reading panels in plant	8.80	1.42	1.42
Sending/writing relocated panel location in plant	1.93	0.62	0.25
Extended search in plant	75.78	1.05	1.05
Scanning/reading panels at site entrance gate	4.08	1.44	0
Checking in at construction site	3.27	0.50	0.50
Sending report to plant	0.81	0	0
Selecting storage area at site	29.86	0	0
Sending/writing panel location at site	1.99	1.24	0.50
Identifying panel location at site	11.19	0.50	0.50
Scanning/reading panels at site	4.48	1.42	1.42
Sending/writing relocated panel location at site	1.90	0.62	0.25
Extended search at site	28.69	1.25	1.25
Total	209.54	14.28	10.62

Table 6
Cost savings for reduced number of missing panels and incorrectly delivered/identified panels.

Cost item	Number of savings	Unit price	Total saving
Remanufactured panels	3	1365.00 $	4095.00 $
Incorrectly shipped panels	8	60.00 $	480.00 $
Incorrectly transferred panels	5	110.00 $	550.00 $

4.2. Cost savings

Cost savings in the RFID cases were observed due to: (1) the reduced number of missing panels, and thus the reduced number of remanufactured panels, (2) the reduced number of incorrectly shipped/identified panels, and therefore, the decreased number of transfers, and (3) the reduced durations of some activities, resulting in decreased labor costs. The total amount of the first two types of cost savings is the same for the SA and FA cases. The only difference is observed in the third type of cost savings.

The first type of cost is related to the remanufacturing of missing components. The production cost of a panel is $1365, including materials, labor equipment and transportation cost. The cost savings for each RFID case was $4095, which corresponds to the cost of three missing panels in the base case.

The second type of cost is the transfer costs, which include: (1) the cost of shipping the produced panel that replaces the incorrectly identified panel from the plant to the construction site by truck; and (2) the cost of transferring the incorrectly delivered panel to the installation location at the construction site by crane. For the investigated project, the unit price of shipping by truck was identified as $60/h, including labor costs. The unit price of the crane is $110/h including the operator cost. The total cost savings for transportation in SA and FA cases was $5125. Table 6 shows the cost savings due to the reduced number of missing materials, incorrect shipment and panel transfers both in the plant and at the construction site.

To calculate the third type of cost savings, which is related to the reduced activity durations, the accumulated time savings of activities for the SA and FA cases were multiplied by the unit price of labor for that activity. Table 7 reports the time savings for the SA RFID case and the FA automated RFID case when compared with the base case. The unit price of a worker was $6/h for this project both in the plant and at the construction site. The identified cost savings are shown in Table 7. The largest time and cost savings were observed in the extended search activities as these activities have the largest accumulated time savings.

When the cost savings are compared for SA and FA RFID cases, the difference in cost savings of these two RFID cases are not significant because: (1) the cost savings due to the reduced number of missing panels and incorrectly delivered/identified panels are the same for both cases; and (2) the total time savings for 150 panels in the FA RFID case is 3.7 h more than the total time savings of the SA case. The corresponding cost savings is $22.2 for 150 panels and $518 for 3500 panels, which is the total number of panels produced for the investigated project. As seen in Table 7, 3.7 h in savings results from "sending/writing panel location in plant and at the construction site" and "scanning/reading panels at site entrance gate" activities. The FA case requires multiple antennas at the entrance gate, and a reader integrated with an antenna on each forklift. Also, to send the coordinates of the panels to the database, a weight sensor and a GPS receiver need to be installed on the forklift. As the cost of this additional equipment will be higher than the cost of savings received, for this investigated case the SA RFID approach is identified as a more economical solution. However, if this equipment is used in multiple projects, the FA RFID approach might be more feasible.

For the SA RFID case, the cost savings incurring from the labor hours are calculated as $1172 for 150 panels. For the investigated project, 3500 pieces of panels were produced and the total labor cost saving for 3500 panels was $27,356. The total cost savings due to the reduced amount of missing materials was $95,550, and the total savings resulting from the decreased number of transfers was $24,033 for all of the panels used in the project. To conclude, the total cost savings for the examined project was $146,939 if SA RFID technology is integrated into current material tracking systems. This accounts for 3.1% of the total price of the investigated project (i.e. the total cost of 3500 panels). 19% of the total cost saving is due to reduced labor costs, 65% from the reduced amount of missing materials (i.e., remanufacturing) and 16% from the reduced number of transfers.

4.3. Cost sharing ratio

To calculate the cost sharing ratio, the cost savings were assigned to each related party based on who would benefit from the cost saving. In other words, the cost savings that occur in the plant and during shipping to the site are attributed to the panel manufacturer whereas the savings that occur at the construction site are included in the contractor's savings. Finally, the ratio of cost savings for each party is determined to calculate the cost sharing ratio.

For the plant and the construction site, cost savings for the SA case are calculated and presented in Table 8. The total cost savings

Table 7
Time and cost savings for the SA RFID and FA RFID cases for 150 panels.

Activity	Time savings		Cost savings	
	Base case vs SA RFID	Base Case vs FA RFID	Base case vs SA RFID	Base case vs FA RFID
Writing RFID tags/labels	−1.2 h	−1.2 h	−7.2 $	−7.2 $
Selecting storage area in plant	11.6 h	11.6 h	69.6 $	69.6 $
Sending/writing panel location in plant	0.7 h	1.4 h	4.2 $	8.4 $
Identifying panel location in plant	21.5 h	21.5 h	129 $	129 $
Scanning/reading panels in plant	7.4 h	7.4 h	44.4 $	44.4 $
Sending/writing relocated panel location in plant	1.3 h	1.7 h	7.8 $	7.8 $
Extended search in plant	74.7 h	74.7 h	448.2 $	448.2 $
Scanning/reading panels at site entrance gate	2.6 h	4.1 h	15.6 $	24.6 $
Checking in at construction site	2.8 h	2.8 h	16.8 $	16.8 $
Sending report to plant	0.8 h	0.8 h	4.8 $	4.8 $
Selecting storage area at site	29.9 h	29.9 h	179.4 $	179.4 $
Sending/writing panel location at site	0.8 h	1.5 h	4.8 $	9 $
Identifying panel location at site	10.7 h	10.7 h	64.2 $	64.2 $
Scanning/reading panels at site	3.1 h	3.1 h	18.6 $	18.6 $
Sending/writing relocated panel location at site	1.3 h	1.7 h	7.8 $	10.2 $
Extended search at site	27.4 h	27.4 h	164.4 $	164.4 $
Total	195.4 h	199.1 h	1172.4 $	1194.6 $

Table 8
Cost savings at the plant and at the construction site ($) (Comparison of base case and SA RFID case).

Location	Task durations	Remanufactured panels	Incorrect shipping/ identification	Total
Plant	696	2730	480	3906
Site	476	1365	550	2391

was calculated as $6297 for 150 prefabricated precast concrete panels that are produced in 5 months. A $3906 cost savings occurred at the plant and $2391 at the construction site. Based on these benefits, the cost sharing ratio was calculated at 0.62 for the manufacturer and 0.38 for the contractor. The identified cost sharing ratio for the two parties can be used to distribute the cost of RFID investment in the described supply chain. The same approach can be used for other RFID and ADCT implementations in construction supply chains to distribute the investment cost.

5. Sensitivity analysis

The purpose of the sensitivity analysis was: (1) to determine whether the simulation will yield similar results if the input values that are entered in the model have some uncertainties and differ from the actual values; and (2) to understand whether the simulation model works as designed. To identify the sensitivity of the simulation results, changes in the probability of finding the panel in the extended search is examined, since this critical parameter can vary based on the worker's capabilities and site conditions. The extended search at the plant is performed when a panel cannot be located either at the plant or at the construction site. The change in the probability of this action directly affects the number of following activities performed in the simulation: identifying the panel location in the initial search at plant and reading the panel at the site entrance gate during the receiving process. When the percentage of found panels in an extended search decreases, more panels need to be remanufactured, and the number of components identified at the storage yard increases. Also, the panels that cannot be located at site are also looked for in an extended search at the plant. Moreover, when more panels are remanufactured, more panels are shipped to the construction site; increasing the number of received components.

The probability of finding a panel in the extended search at the plant was determined to be 97% for the base case, according to the interviews conducted with the practitioners. During the sensitivity analysis, different probability values (i.e., 90%, 85%, 75% and 10%) were entered as an input in the model and the change in the number of missing panels was investigated. Table 9 compares the results of the base case and the SA RFID case for different probability values and, shows how the change in the probability of finding a panel in the extended search affects the benefits and the cost sharing ratio of the parties.

The results show that if the probability is within the range of 85–97%, the cost sharing ratio is similar for both the manufacturer (i.e., 70% and 62%) and the contractor (i.e., 30% and 38%). While there were three missing panels (i.e., two at the plant, one at site) in the first case (e.g., 97% probability), eleven panels (i.e., eight at the plant, three at site) were missing in the second case (e.g., 85% probability). A drastic change is observed in the cost sharing ratio of both parties when the probability is equal to or less than 75%: the manufacturer receives four times more benefits than the contractor. The sensitivity analysis demonstrated that the cost of the missing panels affects the manufacturer more than the contractor and the cost sharing ratio does not change drastically if the probability of finding a panel in an extended search is between 85 and 97%. Moreover, when the probability of finding a panel in the extended search decreases, the number of missing panels increases, and the manufacturer receives more benefits and a larger cost share than the contractor. This shows that the model performs as designed.

6. Conclusions

In this study a simulation-based tool was used to model the exterior concrete panel supply chain and to identify the benefits and related cost savings for calculating a cost sharing ratio among different parties (i.e., manufacturer and contractor) in a supply chain. The supply chain was modeled as a two-echelon supply chain, including the prefabrication and construction phases. Three simulation models were developed to compare the current manual approach (i.e., base case) with RFID integrated supply chains (semi-automated (SA) and fully-automated (FA) RFID cases).

An important result of this study showed that new technologies, such as RFID, can lead to high productivity gains: 93% for the investigated case for the operational activities (i.e., identification and locating). According to the simulation results, incorrect shipments and missing panels were eliminated by the utilization of RFID technology. Also, a significant reduction was observed in the accumulated duration of the activities related to the use of this technology, such as the identification of panel locations in the plant and extended searches.

Cost savings in the RFID cases were observed due to: (1) the reduced number of missing panels, and thus the reduced number of remanufactured panels; (2) the reduced number of incorrectly delivered/identified panels, and therefore, the decreased number of transfers; and (3) the reduced durations of some activities, resulting in decreased labor costs. The total cost savings calculated for the investigated project was $146,939 for the SA RFID technology. When the total price of the investigated project (i.e., the total cost of 3500

Table 9
Cost savings at the plant and at the construction site for different probability values of finding a panel in the extended search in plant (for 150 panels).

Probability value	Location	Task durations ($)	Remanufactured panels ($)	Incorrect shipping/identification ($)	Total ($)	Cost share
97%	Plant	696	2730	480	3906	62%
	Site	476	1365	550	2391	38%
	Total ($)	1172	4095	1030	6297	
90%	Plant	716	6825	480	8021	68%
	Site	472	2730	550	3755	32%
	Total ($)	1191	9555	1030	11,777	
85%	Plant	732	10,920	480	12,132	70%
	Site	474	4095	550	5120	30%
	Total ($)	1206	15,015	1030	17,252	
75%	Plant	763	20,475	480	21,718	81%
	Site	476	4095	550	5120	19%
	Total ($)	1238	24,570	1030	26,838	
10%	Plant	1045	98,280	480	99,805	89%
	Site	474	10,920	550	11,944	11%
	Total ($)	1519	109,200	1030	111,749	

panels) is considered, this cost saving accounts for the 3.1% of total project cost. More than the half of the cost saving (i.e., 65%) resulted from the reduced amount of missing materials (i.e., remanufacturing), and the amount of cost savings for reduced labor costs and the reduced number of transfers were almost equal (i.e., 19% and 16%, respectively).

It is observed that the differences between the cost savings of the two RFID-based cases are not significant. For this particular case, the SA RFID approach was determined to be a more cost-effective approach since the FA RFID case requires additional equipment that costs more than the cost savings received. However, if this equipment is used in multiple projects, the FA RFID approach might be more feasible.

The cost sharing ratio for the manufacturer and the contractor was calculated at 0.62 and 0.38, respectively, based on the related cost savings. The calculated cost sharing ratio can be used to distribute the cost of RFID investment between the parties in the described supply chain. The same approach for calculating the cost sharing ratio can be used for other RFID implementations in construction supply chains to distribute the investment cost. As future work, validation of SA and FA RFID models can be achieved by testing the proposed approaches in a real-life project. Furthermore, a cost–benefit analysis can be performed and the investment cost of both RFID methods can be calculated to determine whether it is cost-efficient to implement the suggested technologies in a supply chain.

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