

---

This is an electronic reprint of the original article.  
This reprint may differ from the original in pagination and typographic detail.

Zhao, Jianyu; Seppänen, Olli; Peltokorpi, Antti; Badihi , Behnam; Olivieri, Hylton  
**Real-time resource tracking for analyzing value-adding time in construction**

*Published in:*  
Automation in Construction

*DOI:*  
[10.1016/j.autcon.2019.04.003](https://doi.org/10.1016/j.autcon.2019.04.003)

Published: 01/08/2019

*Document Version*  
Publisher's PDF, also known as Version of record

*Please cite the original version:*  
Zhao, J., Seppänen, O., Peltokorpi, A., Badihi , B., & Olivieri, H. (2019). Real-time resource tracking for analyzing value-adding time in construction. Automation in Construction, 104, 52-65.  
<https://doi.org/10.1016/j.autcon.2019.04.003>

---

This material is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.



# Real-time resource tracking for analyzing value-adding time in construction

Jianguo Zhao<sup>a,\*</sup>, Olli Seppänen<sup>a</sup>, Antti Peltokorpi<sup>a</sup>, Behnam Badihi<sup>b</sup>, Hylton Olivieri<sup>c</sup>

<sup>a</sup> Department of Civil Engineering, Aalto University, P.O. Box 12100, FI-00076 Aalto, Espoo, Finland

<sup>b</sup> Department of Communications and Networking, Aalto University, Espoo, P.O. Box 15400 (T building)/15500 (Maarintie 8 building), FI-00076 Aalto, Finland

<sup>c</sup> Racional Engenharia, Av. Chedid Jafet, 222, Bloco D, 3° andar, São Paulo, Brazil

## ARTICLE INFO

### Keywords:

Real-time tracking  
Production control  
Construction  
Data analysis  
Value-adding time

## ABSTRACT

Improving the effectiveness of production control has attracted the interest of researchers and lean construction practitioners over recent years, through techniques such as Last Planner System (LPS) and Location-based Management System (LBMS). However, in these techniques, data collection and analysis still remain manual. Remotely locating workers on site has been suggested as a potential technology to collect crucial data required for production control. The purpose of this study is to test the applicability of a real-time tracking system for collecting data for production control in different types of construction projects. We applied Bluetooth Low Energy (BLE) technology in real-time tracking of workers in three case projects, including residential, office building, and plumbing renovation. We compared various tracking device placement strategies and analyzed the share of uninterrupted presence of workers in work locations based on the collected data. The findings show that both location-based and time-based information of workers can be obtained in real time from the proposed system, but issues of accuracy and coverage need to be considered when defining the data collection plan for each project. Accuracy and coverage issues can be resolved to a significant degree by applying heuristics in data analysis rather than investing in a more sophisticated tracking technology. The conclusion is that real-time tracking technologies are ready for implementation when certain heuristics and guidelines for installation are followed. It is possible to calculate a real-time presence index on a construction site. These data could be used to evaluate the impact of construction management interventions on waste on-site.

## 1. Introduction

Complexity is a term often used when discussing construction projects and their on-site management. Projects comprise many interconnecting parts during the process [1] and have poor reputation for managing risks with failure to meet deadlines and cost targets [2], which is compounded by demanding time constraints and low work efficiency [3]. The on-site complexity has led to the development of production control techniques that can reduce variability in workflows [4]. Among these techniques, Last Planner System (LPS) [5], Location-based Management System (LBMS), and their combinations [6] stand out, aiming to improve the utilization of resources, reduce project durations, and define more accurate production forecasts [7].

The existing techniques tackle the problem of complexity in production control through systematic data collection and use in evaluation and estimation—for example, Critical-path Method (CPM) is used for monthly schedule updates, including estimates of remaining work resulting in understanding of critical tasks of the project [8]; LBMS is

used for weekly routines to collect actual start and finish dates, percentage completed and actual resources; and LPS is used for recording the percentage of work completed or tracking percent plan completed (PPC) verbally in meetings [6]. However, data for all these activities has still traditionally been manually collected and entered into the system, and most analyses of labor productivity are still done manually [9]; this is time-consuming, subjective to judgements, and prone to error [10]. There are recent attempts to automate data collection on production resources and status using sensor technologies, such as Radio-frequency Identification (RFID) [9], Magnetic Field [11], ZigBee [12], and BLE (Bluetooth Low Energy) [13]. Vasenev et al. [14] suggest a framework that connects the sensor data collection from various sources to decision-making at the operational, tactical, and strategic levels.

Despite the suggested technologies and their applicability tests in recording important project data for production control (e.g. [9]), there is scarce research that shows how a real-time tracking system can be used for identifying value-adding time of construction resources. As

\* Corresponding author at: Department of Civil Engineering, Aalto University, P.O. Box 12100, FI-00076 Aalto, Espoo, Finland.

E-mail addresses: [Jianguo.zhao@aalto.fi](mailto:Jianguo.zhao@aalto.fi) (J. Zhao), [olli.seppanen@aalto.fi](mailto:olli.seppanen@aalto.fi) (O. Seppänen), [antti.peltokorpi@aalto.fi](mailto:antti.peltokorpi@aalto.fi) (A. Peltokorpi), [behnam.badihi@aalto.fi](mailto:behnam.badihi@aalto.fi) (B. Badihi).

<https://doi.org/10.1016/j.autcon.2019.04.003>

Received 29 June 2018; Received in revised form 11 January 2019; Accepted 4 April 2019

0926-5805/© 2019 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

LPS, LBMS, and their combinations finally aim at reducing waste (or increasing added value), the fundamental issue is how real-time tracking does not only improve production control but also enables measuring of the performance level of site operations. Waste can occur in many ways—such as waiting, transportation, or movement [15]—and crucial requirement for a tracking system is to identify these non-value-adding activities, which are not often noticed in the project [16]. Previously value-adding time and waste have been analyzed by observing workers (e.g. [17,18], or asking the workers by conducting a survey (e.g. [16,19]) or an interview study [20]. The problem with observation is that while accurate, it cannot be employed in real-time or at a large scale due to the requirement of having one observer for each worker or crew of workers. Surveys and interviews are based on the subjective opinions of each worker and the workers tend to underestimate waste, considering many wasteful tasks, such as material logistics, as being ones that are value-adding [6]. Kalsaas [17] implemented both observations and a survey study and found that self-reported waste was different from observed waste.

A scalable system that could measure waste on worker, sub-contractor and project level could provide significant benefits to an industry plagued with poor productivity. Presence in work location for longer continuous time periods is a necessary condition for value added time and thus is at least correlated with value added time, although not all time the workers spend in work locations is necessarily value adding. Therefore, this research explores how real-time tracking of on-site resources can enable identification of uninterrupted work location presence in construction in an automatic and scalable manner. Comprehensive tests in multiple projects are needed to answer this question because project-specific space layouts and building materials may affect data coverage and accuracy. To ensure scalability and ease of implementation, the system should be easy to deploy with minimum context-based setup time required.

In this research, we focus on the indoor construction phase and relate indoor location technologies because, from the production control perspective, that phase is often the most chaotic (e.g. [21,22]). Identifying work location presence using automated data collection and analysis, the system enables monitoring production performance on a daily basis. It would also enable construction management research to move beyond time-consuming observations or subjective methods such as interviews to using automatically collected big data when drawing conclusions regarding outcomes of interventions.

## 2. Real-time tracking for presence analysis on a construction site: previous research

To improve the efficiency of traditional production control methods in construction, researchers have explored and suggested the use of real-time tracking technologies and applications for resources in indoor locations. Many of these technologies are similar to applications in other fields, such as indoor navigation [23] or roadway work zones [11]; however, our analysis focuses on indoor location applications in building construction sites and their contribution to value-adding time analysis.

The identified technologies used for resource tracking in a construction site or similar environments can be divided into passive RFID [9,11], magnetic field [11], ZigBee [24], BLE [11,13,25,26] and Global Positioning System (GPS) [27] solutions. GPS technology is suitable and efficient for outdoor spaces [27], but not as good for indoor use as satellite radio signals cannot penetrate solid walls and indoor obstacles [24]. Furthermore, indoor positioning systems (IPSSs) may vary substantially in terms of accuracy, cost, precision, technology, scalability, robustness, and security [28]. Those factors contribute to the difficulties of indoor positioning compared to outdoor positioning due to the complexity of indoor environment [29]. With RFID, the scale of accuracy problem is smaller than with BLE as readers can be more easily placed near working space exits, such as next to the elevators [9]. In a

dam project of open spaces, Lin et al. [12] conducted the localization accuracy analysis based on a field test using ZigBee and concluded that the tracking accuracy of that technology is 3–5 m. They used signal strength indicator (RSSI) [30] implemented on ZigBee devices in the outdoor project, but data accuracy has not been examined in an indoor construction environment. In addition, Cheng et al. [31] propose the integration approach by using data from both real-time location sensors (RTLS) and thoracic accelerometers, using data fusion to achieve a deeper level situation picture about worker's activities on-site. From the system implementation perspective, it appears that BLE technology requires a lower amount of infrastructure and time for calibration than, for example, RFID and magnetic field [11]. Integrated systems (e.g. [31]) appear to be the most accurate in detecting resources and even activities; however, their implementation and algorithms for integrating data from different sources requires remarkable investments for each activity to be considered. In summary, from the implementation perspective, BLE technology is most cost-effective and also appears to be sufficiently accurate for further consideration in scalable work location presence analysis.

Despite the potential of applying BLE technology in real construction projects, existing research mentions a few problems regarding its accuracy in the construction site environment. Park et al. [25] argue that the BLE system is often unreliable in terms of detecting workers or other resources between the zones, as the test only showed reliable signal communication when beacons were spaced not more than five meters apart. This may complicate presence analysis, as it might be difficult to define whether a worker is in an appropriate location. Zhao et al. [26] add on to this by highlighting the role of the gateway placement strategy in BLE solutions. Placing gateways that collect Bluetooth signals next to the entries and exits of working zones can improve the accuracy of resource location.

Most of the use cases regarding real-time resource tracking focus on safety management or productivity measurement (e.g. [32,33]). Even if safety management applications cannot be directly utilized in presence analysis, they reveal certain relevant concepts and issues that have value for further consideration. For example, Lin et al. [12] emphasize the concept of worker behavior, which can be detected not only on the basis of worker location but also based on other issues occurring simultaneously, such as the location of other workers or equipment. Similarly, the value-adding time of a worker may be related to the simultaneous status of corresponding materials and equipment if a worker is, for example, carrying material or using an equipment. Zhao et al. [26] propose similar ideas, but without evidence from actual projects.

With regard to value categorizations, previous studies suggest using real-time tracking when differentiating value-adding assembly or working time from movement, idle time, and material-related tasks [9,31]. These categories fit well with Ohno's [15] waste sources related to movement, transportation, waiting, or overproduction. Moreover, inappropriate inventory can be detected if material resources or sub-products are tracked. Costin et al.'s [9] method is limited to analyzing workers entering and exiting a floor using an elevator. However, wasteful movement can happen on the floor, so a more detailed measurement is required. In addition, not all projects have a similar setup where an elevator can be used to define value-adding work. The method is promising but does not appear to generalize several project types and cannot separate value-adding time and non-value adding time within the building. Cheng et al.'s [31] research combined worker's motion speed and posture status to reveal the assembly task of a worker. However, each type of detected activity requires separate training of the algorithms and a large data collection effort. Moreover, researchers have explored the possibilities of more precise detection of posture of workers by applying accelerometer-embedded wristband or site surveillance videos [34,35], however, the systems require significant amount of training data, resources and infrastructure. Therefore, in our research, we focus on more holistic and lighter-weighted technologies,

**Table 1**  
Previous research and conclusions for value analysis.

Article	Technology	Main results	Conclusions directing our study
Park et al. [11] Performance Test of Wireless Technologies for Personnel and Equipment Proximity Sensing in Work Zones	RFID, magnetic field, and BLE	Technologies were compared. The BLE system provided the highest level of simplicity with its minimized infrastructure.	BLE is a promising technology for tracking workers and equipment both from reliability and easy-to-use perspectives The study focused on safety issues in roadway work; thus, gaps exist in terms of how to apply in indoor construction for presence analysis.
Lin et al. [12] Real-time Monitoring System for Workers' Behavior Analysis on a Large-Dam Construction Site	ZigBee tracking utilizing fingerprinting software	Study the feasibility of a real-time monitoring system to provide prompt analysis support of workers' behavior on dam construction sites.	Understanding worker behavior based on location and other timely information on context may be a key in revealing value-adding time. The ZigBee is an appropriate system to improve safety in dam construction. However, it is not clear how to use in indoor construction for presence analysis.
Costin et al. [9] Leveraging passive RFID technology for construction resource field mobility and status monitoring in a high-rise renovation project	RFID	Propose a passive RFID technology to measure the utilization rate of resources by analyzing their tracked time stamp information.	RFID time stamps can be used to reveal travel times and wait times for elevators, which are remarkable non-value adding activities in high-rise buildings. Discrepancy between whole daily work time and identified time on a given floor enables the calculation of workplace presence. However, the solution only works on projects where floor access is controlled and is limited to floor level of detail.
Cheng et al. (2013) Automated task-level activity analysis through fusion of real time location sensors and worker's thoracic posture data	Ultra-Wideband (UWB) and Physiological Status Monitors (PSMs)	The paper proposed a framework for identifying and understanding worker's activity type and productivity over time	For worker value-adding time analysis, material, travel and idle times should be differentiated from work time. Worker's motion speed and posture status may reveal ongoing activity and whether or not it is value adding. Tested technology is sophisticated and has plenty of potential. However, its applicability in less repetitive assembly work and installation at the project level is questionable due to the need to train algorithms for each specific activity at an individual level.
Park et al. [25] Framework of Automated Construction-Safety Monitoring Using Cloud-Enabled BIM and BLE mobile Tracking Sensors	BLE	The system successfully demonstrated the capability to detect unsafe conditions and analyze the trajectories of workers with respect to safety hazards.	BLE system may be unreliable at zone boundaries, thereby complicating value analysis. The study was implemented under the scope of safety control and did not discuss the improvement of production control or analysis of value-adding time.
Luo et al. [34] Towards efficient and objective work sampling: recognizing workers' activities in site surveillance videos with two-stream convolutional networks	Site surveillance videos	The paper introduced an activity recognition method, which produces diverse and continuous activity labels of individual workers onsite.	The study identified activities based on posture recognition from site surveillance videos. However, it only considered masonry work and the method requires extensive training data for each detected activity and manual work in specifying bounding boxes of workers.
Olivieri et al. [13] Real-time Tracking of Production Control: Requirements and Solutions	BLE	The paper proposes a real-time production control system with goals of improving productivity and lower waste on-site.	BLE-based resource tracking may be suitable for evaluating value-adding time. However, the system has not been implemented in the actual environment.
Zhao et al. (2018) Data analysis on applying real time tracking in production control of construction	BLE	The paper implemented the BLE system in a lab test and suggests several use cases.	The gateway placement affects data accuracy and usability. Entry/exit placements can detect movement from and to a value-adding zone. Connecting worker location with material and equipment location may reveal the value of the activity. The system was not tested in actual construction projects.

particularly on BLE technology, and its use in revealing rough estimates of the share of uninterrupted workplace presence of all tracked workers for improved production control. Table 1 summarizes the previous researches on different tracking technologies and presents conclusions from these studies that direct our empirical study on value-adding time analysis.

In summary, previous research suggests that BLE technology might be an appropriate solution for resource tracking in indoor construction. However, more knowledge is needed on how accuracy and coverage problems are solved when using BLE tracking solutions in different types of building construction projects and how value-adding time can be detected from that data. To address this problem, in the empirical

portion of this paper, we utilize and further develop the BLE-based tracking system presented by Olivieri et al. [13] and Zhao et al. [26]. In this system (Fig. 1), construction workers, materials, and equipment carry beacons that transmit tracking data to gateways via BLE technology (links 1, 2, and 3). The signal strength received by the gateways enables the system to identify the current location of the beacon. The cloud-based system analyzes the tracking data and returns the information on a web-based application that shows and updates location details in real time (links 4 and 5).

Following the proposed system framework [13], a laboratory test was conducted in which real-time tracking data was collected and possible use cases for production control have been discussed [26]. In

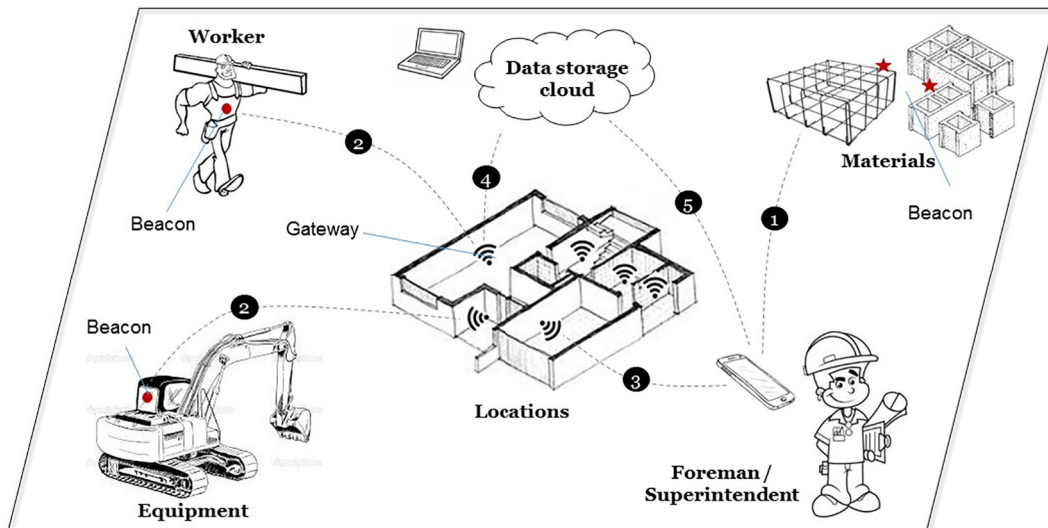


Fig. 1. Proposed real-time tracking scheme on a construction site (adopted from [13]).

this research, we further test and develop the solution with multiple different actual projects aiming at a solution that enables assessing location presence of workers and other resources for improved production control. The following are the relevant open questions for our empirical research:

- 1) How can a real-time tracking system based on BLE technology be applied to different real-size construction projects?
- 2) What is the accuracy and coverage of tracking data and how can it be improved?
- 3) How can the share of uninterrupted presence of project resources be estimated based on real-time tracking data?

### 3. Methods and analysis

#### 3.1. Research process

We followed the design research approach employed in [36]. The proposed research methods, steps, and goals are summarized in Table 2. A case study research method is applied for the study because it explores a contemporary phenomenon within real-life contexts when “why” or “how” questions are being posed [37]. In this research, we aim to answer how the proposed system can be implemented in actual construction projects and to discover how the accuracy of the data can be evaluated and improved in order to estimate uninterrupted work location presence on a project level. Therefore, the case study approach

is an appropriate research method.

The proposed system was validated and improved on the basis of actual case studies in construction projects. The study covered different construction project types in the industry, including a residential building, an office building, and a plumbing renovation project. The three selected project types aim to cover various construction processes.

The case studies followed a series of steps to ensure that the study was performed objectively: (1) The system was set-up on-site according to the floor plans; (2) the researcher simulated work processes on-site, and system data accuracy was examined on the basis of the known movements of researchers (ground-truth data); (3) system coverage was first tested on the basis of researchers' ground-truth data and then project-level coverage of real workers was analyzed; (4) heuristics were proposed to improve coverage of the system; (5) tracking data with heuristics was compared with data without heuristics to analyze improvement; and finally (6)uninterrupted work location presence level was analyzed.

#### 3.2. System and software architecture

In order to track workers and materials, we used BLE beacons. The BLE beacons periodically broadcast information such as the Media Access Control (MAC) address of the device, minor and major number, and the universally unique identifier (UUID) of the device. In this prototype, only the MAC address of the beacons was exploited, and these addresses were associated with the profile information of the

Table 2  
Summary of research methods.

Step 1: Understanding	(i) Identify a relevant problem	1. How can BLE technology based real-time tracking system be applied on different real-size construction projects? 2. What is the accuracy of tracking data and how can it be improved? 3. Can the share of value-adding time in a project be estimated based on real-time tracking of construction resources?	
	(ii) Deep comprehension of the topic	Theoretical references: Lean Philosophy esp. waste, Last Planner System (LPS), Location Based Management System (LBMS), Bluetooth Low Energy (BLE) Indoor Positioning	Case 1: Plumbing renovation; Case 2: Office building; Case 3: Residential building
	(iii) Artefact	Propose how to improve the quality of raw data from real-time tracking so that the data can be used to estimate value-adding time?	
Step 2: Analysis and Development	(iv) Implement and test the solution (case studies)	System implementation in three construction projects	Data analysis and simulation (six steps)      Model refinement
	(v) Theoretical contribution of the solution	Final version of the integrated model: To estimate uninterrupted work location presence of construction projects	
	(vi) Examine applicability of the solution	System implementation in multiple case studies	

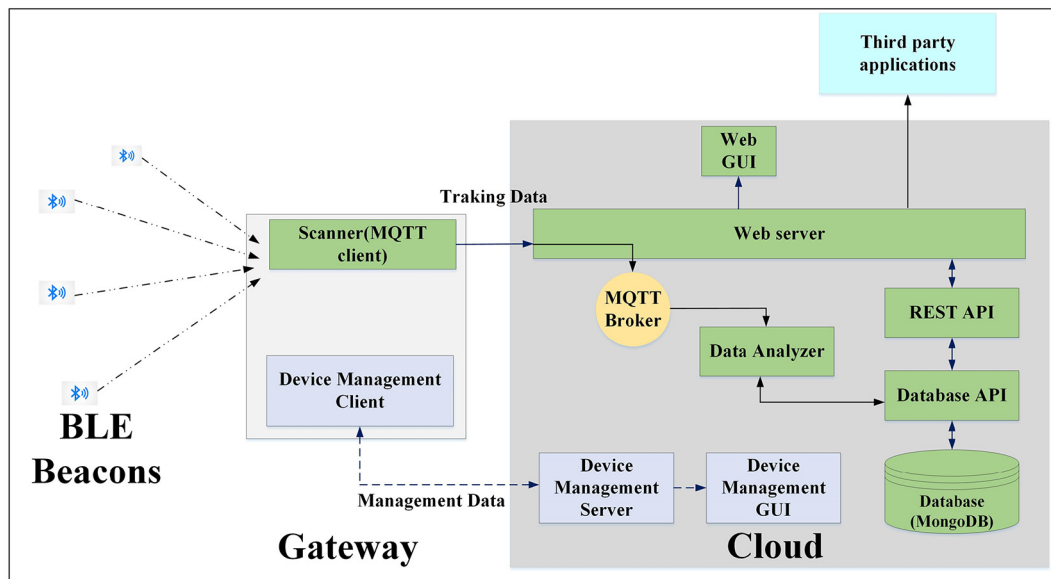


Fig. 2. The architecture of indoor tracking application for construction site.

workers carrying the beacons. The beacons broadcast with the interval of 1 s and the range of the transmission varied from a couple of meters to several tens of meters depending on the transmission power of the BLE beacons. Raspberry Pis were used as a gateway to collect the broadcasted data from the nearby beacons and send them to the cloud. Fig. 2 illustrates the system and software architecture that contains data processing systems, the main data structure and the data flow chart.

The gateways continuously scan the periodic signals from the nearby beacons and transmit them by using Message Queuing Telemetry Transport (MQTT) protocol. The frequency of publishing the data is 1 Hz; in other words, the gateways transmit the data in interval of 1 s. The Broker located in the cloud pushes the data out to those clients that have previously subscribed to a specific topic. In our prototype, Data Analyzer module subscribes to a topic that is published by clients in gateways. In other words, Data Analyzer module consumes the data produced by gateways.

Gateways measure the Received Signal Strength Indication (RSSI) of the signals from the beacons and send RSSIs along with MAC address of each beacon. RSSI is a measure of distance to a gateway: the closer the beacon to gateway, the larger RSSI. This is the criteria used in Data Analyzer to determine the location of beacons.

The method for location used in this prototype is based on Cell of Origin method [24]. In this method, the location of a beacon is determined by the nearest gateway that can hear its signal. This means that if the signal of a beacon is received by several gateways in the vicinity, the gateway that receives the strongest signal is chosen as a beacon's location. The Data Analyzer module compares the RSSI of the beacons and assigns the location of the beacon to a gateway which receives the strongest signal. This value is highly dynamic in the indoor environment and keeps changing due to multi-path propagation of the wireless signal resulting from refraction and reflection in the surrounding environment. Earlier studies have addressed the reliability issue as flickering on real-time tracking [38–40]. To overcome this problem and smoothing out the RSSI values, we utilized an array of  $N$  recent RSSI values of each beacon in each gateway. Storing a new value in the array pushes the oldest one out. By averaging the last  $N$  value of RSSI, the outlier values are removed from the RSSI values and flickering problem is addressed.

The location of each gateway is known, therefore by knowing the fact that beacon belongs to a gateway, the approximate location of the beacon is determined. As the Fig. 2 shows, there are two data flows between gateways and cloud: a) tracking data which is used for location

of the beacons and b) management data which is used for managing, parameter settings and configuring gateways via Graphical User Interface (GUI) of the Device Management module. These two planes of data are independent from one another.

Data Analyzer module is also responsible for storing data to database after the analyzing and filtering job is done. However, this is indirectly executed through a Database API (Application Programming Interface) module. Finally, the data stored in Database can be consumed by a third party application through a REST (Representational State Transfer) API.

### 3.3. Case descriptions and system implementation

Table 3 presents the case descriptions, their respective main objectives, the data collection process, and system setup and maintenance costs. The cases were selected to include properties like small locations (case 1), large open locations (case 2), and tracking at the floor level (case 3). The case studies were initiated by collecting floor plans of each case building and discussing with project teams about where the gateways can be installed. Due to the different size, type, and objective of each project, the numbers of gateways placed on-site varied between projects. This resulted in multiple gateway installment strategies, which will be compared and contrasted in subsequent discussions. During the tracking period, gateways needed to have access to electricity and be constantly connected to the internet. Beacons were distributed to workers who agreed to be tracked by signing an informed consent form to participate in the research. They were instructed on how to use the beacons. Depending on the case study, the number of distributed beacons varied between 11 and 15 depending on project size and the willingness of workers to participate in the research. The beacon transmission power in cases 1 and 3 was kept the default level (12 m), while in case 2 we slightly increased power to achieve the range of 15 m due to large open space in each floor. The goal was to reach a reasonable coverage while minimizing the potential flickering effect.

In the three case studies selected, the variables that change over different construction sites are: (1) numbers of beacons; (2) numbers of gateways; (3) Size of tracking locations; (4) beacon transmission strength; (5) indoor closed environment (e.g. with walls) or indoor open spaces (6) availability of power and connectivity. Over time, additional beacons were registered to the system when new workers started in the project. Ongoing maintenance was required to account for possible changes in the site environment, which sometimes required re-

**Table 3**  
Descriptions of cases and multiple sources of evidence.

Case study/ companies	Project type	Tracking period	Number of tracking devices	Main objective	Multiple sources of evidence	Cost of the hardware (4 EUR/beacon + 55 EUR/gateway)	System setup time and maintenance
Case 1. Fira	Residential building: Plumbing renovation (3318 m <sup>2</sup> )	From September 1 to October 13, 2017	15 beacons to workers; 23 gateways in one jobsite	Worker tracking on apartment level	Biweekly visits to the jobsite to check conditions. Jobsite floorplan. Researcher simulation on-site for data validation.	1325 euro	8 h for system setup; 1–2 h weekly for maintenance
Case 2. YIT	Office building (22,400 m <sup>2</sup> )	From September 21 to November 30, 2017	13 beacons to workers; 21 gateways in one jobsite	Worker tracking in open spaces	Data analysis of tracking results. Four visits to the jobsite for system set-up and condition inspection. Pictures of system set-up. Jobsite floorplan. Researcher simulation on-site for data validation.	1207 euro	6 h for system setup; 1–2 h weekly for maintenance
Case 3. Skanska	Residential building (3869 m <sup>2</sup> )	From October 18, 2017 to January 31, 2018	11 to workers; 10 gateways in one jobsite	Worker tracking at the stairwell and floor levels	Data analysis of tracking results. Three visits to the jobsite for system set-up and condition inspection. Jobsite floorplan. Researcher simulation on-site for data validation. Data analysis of tracking results.	594 euro	5 h for system setup; 1–2 h weekly for maintenance

positioning of the gateways due to changes in the availability of temporary power. However, none of the projects had significant changes in location structure during data collection, such as building interior walls in an originally open space.

Because the appropriate placement of gateways is important for validity of results, we followed a systematic process on the installation and setup of the gateways: (1) obtain floor plans for each case building and mark the preliminary gateway placement based on entrances and exits and natural locations bounded by walls; (2) determine the number of gateways needed and configure the gateways associated with serial numbers in the system; (3) onsite gateway installation based on the installation plan and adjusting for availability of power and connectivity; (4) check if gateways are successfully registered and connected to power and internet; (5) link the gateway serial numbers with the floor plan so that each gateway represents a meaningful location onsite.

### 3.3.1. Case 1 Plumbing renovation

The plumbing renovation case study was located in Helsinki, Finland. The partner company was the general contractor for the selected plumbing renovation project. The simplified section of the jobsite is illustrated in Fig. 3. Work locations were one and two bedroom apartments which were separated with concrete walls and slabs. The total square area was 1106 square meters per floor.

In this project, we attempted to install as many gateways as possible, depending on available power, to ensure that a majority of the apartments would be covered individually by gateways. Gateways were placed along the entrance areas (4 gateways), storage areas (6 gateways), stairwells/corridors between apartments (6 gateways), and inside of apartments (7 gateways). It should be noted that due to the availability of temporary power, some of the apartments had a dedicated gateway while in some floors, one gateway in the corridor served two apartments. Entrances and storage areas were considered locations where no value-adding work was performed while corridors and apartments were considered locations where value was added except for apartment A2 which served as the site office during the observation period.

### 3.3.2. Case 2 Office building renovation

The second case study was an office building renovation in central Helsinki, Finland. The partner company was the General Contractor in this project. The building has seven floors (approximately 2800 square meters per floor) above ground and one floor underground. At the time of the study, the interior walls had not been erected yet, so each floor was an open space. Due to limited access to temporary power, only a few gateways were placed on each floor so that there were areas where beacons could not be detected by any gateway. In this case, the site office did not have a gateway because the social facilities for workers were in the same trailer. Thus, visits to site office in this case study are recorded as offsite time while in other cases the visits to site office are onsite but not in work location. The tests were undertaken after demolition, so the conditions were similar to those of a new construction. The simplified floor plan is presented in Fig. 4. The entrance gateways at the front gate and back gate were considered non-work related because they were next to a storage area and the others were considered gateways in work-related areas.

Since there were open spaces without signal coverage, this project provided an opposite case compared to the plumbing renovation case, where the gateway placements were compact and the signal coverage was comprehensive. By studying the difference, we were able to discuss the impact of gateway placement strategies and suitability of the system in different types of buildings.

### 3.3.3. Case 3 Residential building

The third case study was a new residential building project in Helsinki, Finland. Our partner company was the general contractor in

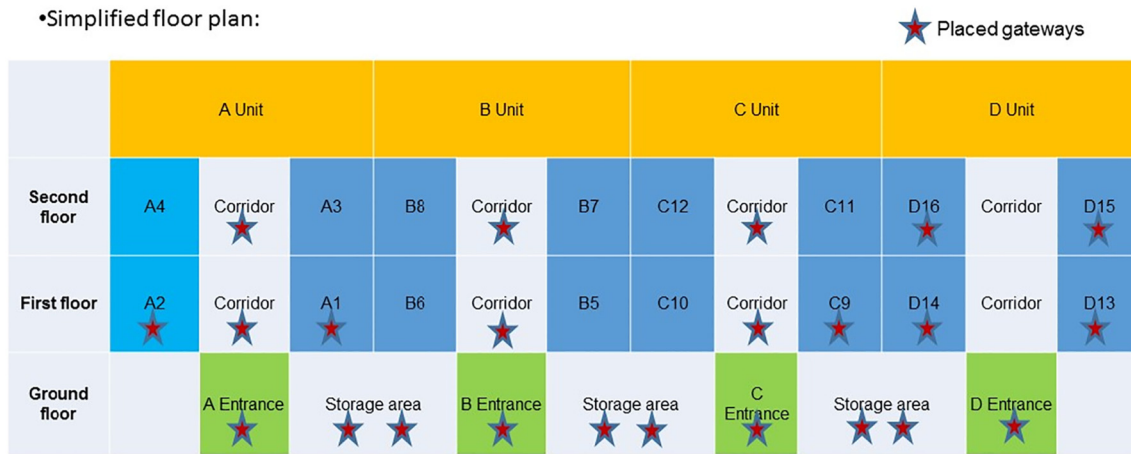


Fig. 3. The plumbing renovation real-time tracking case study schematic plan.

this project. The simplified floor plan is presented in Fig. 5. The building had three stairwells and a construction management office. Each stairwell had five floors. Gateways were placed on each floor of stairwells A and B as well as in the office area. We had two gateways as non-work-related gateways (one in the office and the other in B & C stairwell entry) and others were placed as work-related gateways in the building. At the time of tracking, the entry of A & B stairwells was not open therefore we did not place gateway at A&B stairwells' entry. Construction had not begun on stairwell C, so no gateways were installed there. Cases 1 (plumbing renovation) and 3 are conceptually similar, but the gateway placement in case 3 is at the entrance to each floor while gateways were in apartments in case 1. In both cases, the apartments were separated by concrete walls. The differences between these two cases can shed more light on gateway placement strategies in buildings with concrete separating walls.

### 3.4. Data accuracy analysis

The raw data extracted from the system had the following four attributes: 1) beacon number (carrier information), 2) gateway number (location information), 3) start time at a gateway, and 4) end time at a gateway. Each time interval in the raw data contained these four attributes. A total of 29,877 recordings of time intervals were detected from case 1, 18,620 from case 2, and 3,664 recordings from case 3.

Before beginning to calculate metrics important for production

control, it is necessary to ensure that the system is providing accurate data as a starting point for further analysis. Data accuracy was defined as the capability of the system to detect the tracked objects in the right location at the right time. There are various reasons why the system could report beacons in incorrect locations. For example, if the same beacon was detected by multiple gateways, the signal strength was used to decide where the beacon was. Signal strengths can also fluctuate randomly because of interference. In this research, data accuracy was evaluated by collecting ground-truth data from two researchers who went to construction sites in all the case projects, moved from location to location, and recorded the time they spent in each location. Data accuracy was evaluated by comparing the tracking data in the system to the data self-reported by the researchers. Because the gateway placement strategies in these projects were different, the process was able to provide valuable information on how tracking device placement impacts accuracy (research question 2).

In practice, data accuracy was evaluated on the basis of how many correct and incorrect minutes were recorded in the system when compared with the actual position of the researcher at that minute. Table 4 shows in detail how actual movements were matched with system recordings of one researcher in case 1. Due to the actual conditions of jobsites, some gateways needed to cover multiple apartments; for example, in the “recorded location” column, the gateway “A1A2” is covering both apartments A1 and A2. As long as the recorded location matched any of the actual locations in the same time interval, we

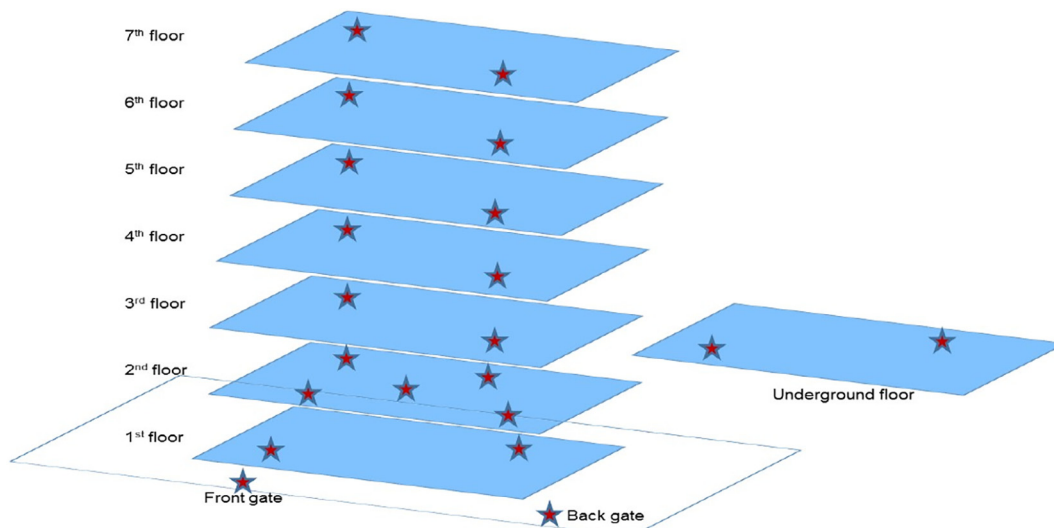


Fig. 4. The office building renovation real-time tracking case study floor plan.



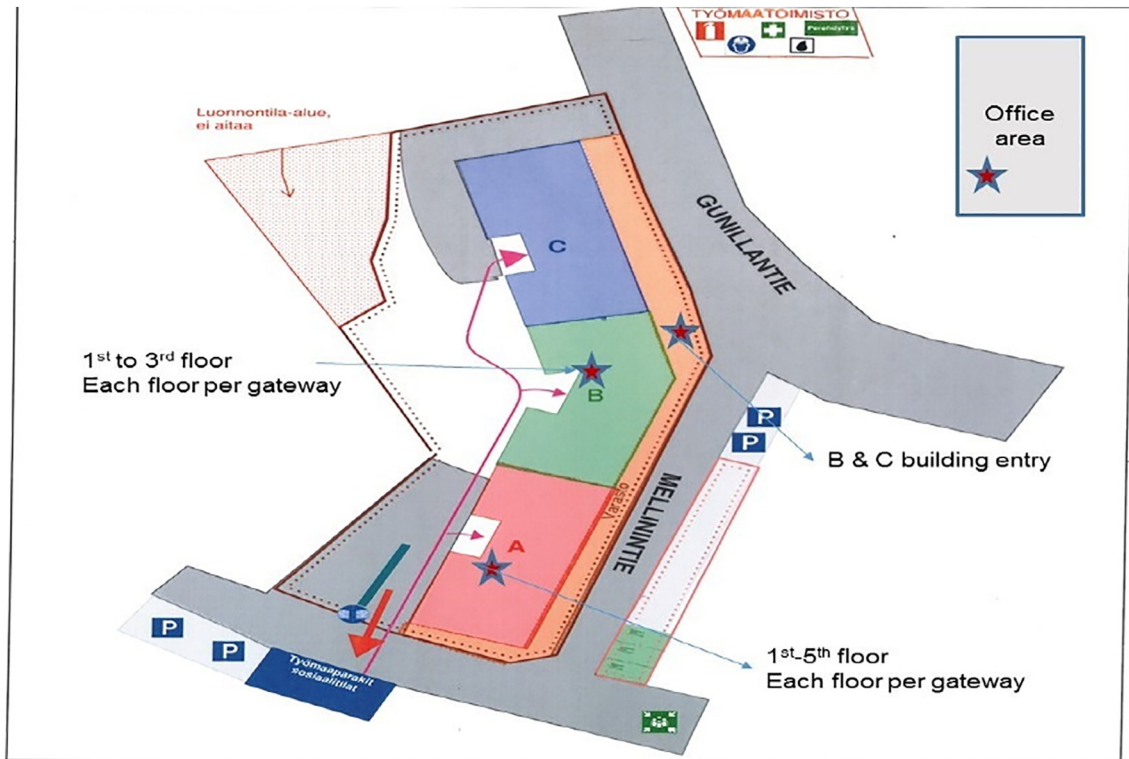


Fig. 5. The residential building case study gateway placement floor plan.

assumed that the time was recorded correctly. For example, if the raw data location in the system was “A1A2” and the actual location of the researcher was “A1,” the time interval was considered correctly recorded in the table. Researchers also moved around during tests, in which case the “actual location” column of the table shows two locations (e.g. A1-C11). In that case, detection was considered correct, if the system recorded any location on the path between the two locations.

To understand the reasons for data inaccuracy, the non-matches were reviewed in detail and categorized. One reason category is that an incorrect gateway detected the beacon for a period of over a minute (non-match category 1). In the second category (non-match 2), the gateways were close to each other, but the incorrect detection was less than a minute. This category can be called flickering, which has often been mentioned as a reliability issue in previous studies on real-time tracking (i.e., [38–40]). The third category (non-match 3) was a coverage problem, in which the beacon was not detected at all.

The results of the data accuracy and coverage analysis of all three cases are presented in Table 5. The total matched time varied substantially between the cases being the highest in case 3 with stairwell and floor level gateway placement in apartment building. Although accuracy and flickering problems were evident—particularly in cases 1 and 3 with denser gateway placement strategies—overall, problems with system coverage were most remarkable. In open space case 2, 55% of the researchers' time on site was not detected at all. In summary, the data coverage rate was unacceptably low for presence time analysis; thus, various ways of improving the coverage were investigated.

### 3.5. Data coverage analysis at worker level

In the data accuracy analysis with researcher validation data, data coverage was identified as a problematic issue to resolve before conducting uninterrupted presence analysis. Coverage of gateways depends on the density of installed gateways, their micro locations and inside environment. For example, concrete walls and slabs can hinder the radio signals thus lowering data coverage.

To evaluate data coverage more deeply, we analyzed the researchers' and workers' location data in all three cases. The “coverage ratio” was defined as the proportion of time the beacon was actually detected out of the total operational time of the day. The total operational time of a worker was the time from the first detection of a beacon on site on a day to the last detection on the same day. The coverage ratio indicates how well the system is covering the job site operations. Workers may leave the site for example to have a break, to go to another project or to visit a hardware store (in case 2, workers can also go to site office which is not under gateway coverage), so their coverage ratio is normally never 100%. However, for researchers performing validation on site, under conditions of perfect coverage, the ratio should be 100%. Table 6 presents the detected time, total operational time, and coverage ratios in cases 1, 2, and 3 compared with the overall researcher coverage ratio.

Compared to researcher movement analysis, the project workers' overall coverage ratios are lower on average. This is expected because workers can be genuinely off site, for example, running errands in hardware stores. In addition, social facilities did not include gateways, except in project 1 where the site office was in one of the apartments and also served as a break room for workers. Therefore, the expected maximum coverage ratio was approximately 88% (510 min minus 60 min of breaks) in projects 2 and 3, and 100% in case 1 where workers could have all their breaks in areas covered by gateways. In case 2, the site office did not have gateway which could be one of the reasons that case 2 reached a very low coverage degree. In summary, the actual coverage ratios were quite low, thereby indicating either substantial off-site time or incorrect detection. This leads to problems when calculating project-level uninterrupted work location presence (research question 3). The conclusion of the coverage analysis is that (1) there is a need to develop some heuristics to improve the coverage ratio and (2) gateway placement can substantially affect the coverage ratios so finding a good placement strategy for each project is critical to ensure the quality of data. Next, we focus on ascertaining how the coverage could be improved by implementing heuristics in the system.

**Table 4**  
A researcher's actual and recorded locations: an example of the case 1.

Time	Duration (minutes)	Actual location	Recorded location	Category
8:21–8:24	3.2	A entrance	A entrance	Match
8:24–8:27	2.4	A2	A1	Non-match 1
8:27–8:29	2.0	A2	A2	Match
8:29–8:29	0.4	A2	A1A2	Match
8:29–8:30	1.0	A2	A1	Non-match 2
8:30–8:31	0.8	A2	A2	Match
8:31–8:31	0.7	A2	A1	Non-match 2
8:31–8:33	1.6	A2	A2	Match
8:33–8:36	3.0	A1	A1	Match
8:36–8:36	0.1	A1	Not detected	Non-match 3
8:36–8:38	1.4	A1	A1A2	Match
8:38–8:39	1.6	A1	Not detected	Non-match 3
8:39–8:40	1.0	A1	A2	Non-match 2
8:40–8:41	0.8	A1	Not detected	Non-match 3
8:41–8:44	3.1	A1-C11	A2	Non-match 1
8:44–8:47	2.8	C11	C11C12	Match
8:47–8:50	3.1	C11	Not detected	Non-match 3
8:50–8:52	2.2	C11	C11C12	Match
8:52–8:56	3.7	C11	Not detected	Non-match 3
8:56–9:01	5.2	C11-A2	C11C12	Match
9:01–9:02	1.1	C11-A2	C entrance	Match
9:02–9:03	0.5	C11-A2	A1A2	Match
9:03–9:05	2.7	C11-A2	A1	Non-match 3
9:05–9:23	18.0	B5	B5B6	Match
9:23–9:24	1.2	B5	B entrance	Non-match 1
9:24–9:25	0.4	C12	C entrance	Non-match 2
9:25–9:25	0.3	C12	C9C10	Non-match 2
9:25–9:27	2.0	C12	C11C12	Match
9:27–9:28	0.5	C12	C entrance	Non-match 2
9:28–9:29	1.1	D12	D entrance	Non-match 1
9:29–9:35	6.1	D14	Not detected	Non-match 3
9:35–9:40	4.7	Ground floor	D entrance	Match
9:40–9:43	3.2	Ground floor	Not detected	Non-match 3
9:43–9:44	0.9	Ground floor	B entrance	Match
9:44–9:44	0.5	Ground floor	A1	Non-match 2
9:44–9:46	2.2	A2	A2	Match
9:46–9:55	8.7	A2	Not detected	Non-match 3
9:55–9:56	0.5	A2	A2	Match

3.6. Improving coverage through heuristics

A heuristic technique was adopted as a method to solve the identified system coverage problem. The practical aim of using heuristics was to identify systematic patterns of how to define the location of a worker during those time intervals in which his or her beacon is not detected by the system. To develop systematic patterns, the researcher movement data from cases 1, 2, and 3 were used as raw material by comparing system data and manually registered data in uncovered situations. In this manner, data were observed in detail to identify heuristics that could improve the results with a minimum level of additional data required on the context of the construction project.

We reasoned that non-detected time could result from two reasons: 1) true offsite time when workers are away from site, and 2) time that workers are actually on site moving or working but are not detected by any gateway (real coverage problem). If gateways are located at each possible entrance and exit of the building, a reasonable assumption is that if a worker is last seen at an exit and then disappears from the

**Table 5**  
The data accuracy analysis: summary of the researchers' locations in the three cases (all times in minutes).

Project	Total matched time	Total time of "non-match" category 1 (Accuracy)	Total time of "non-match" category 2 (Flickering)	Total time of "non-match" category 3 (Coverage)
Case 1. Plumbing renovation	52 (55%)	11 (11%)	4 (5%)	27 (29%)
Case 2. Office open space renovation	37 (41%)	4 (4%)	0.02 (0%)	50 (55%)
Case 3. Apartment building	54 (74%)	8 (11%)	3 (4%)	8 (11%)

system, the worker is off-site. Similarly, if a worker disappears at a non-exit location, the worker is more likely still in the building. This simple heuristic requires context information on the location of gateways either in the exit or non-exit location. Table 7 presents possible scenarios of this heuristic rule.

The following are the four possible scenarios:

- 1) If a worker disappears at an exit location and later reappears at an exit location, the offsite time can be considered "true off-site time" and it is reasonable to assume that the beacon is actually off-site (Scenario 1).
- 2) In any other combination of gateways (Scenarios 2, 3 and 4), it is reasonable to assume that the worker has spent time on the locations of both gateways regardless of their type, and the undetected time can be divided evenly among those locations.

Since we knew the actual movement of the researcher on-site testing the accuracy of the system, we first used that data to see how heuristics affect the data quality. Table 8 shows the improvement in coverage ratios in each of the cases after running the heuristics. The coverage ratios increased in all cases. The findings also indicate that the system's coverage in the open space project with sparse gateway placement is lower also after heuristics than in the cases with more compact gateway placement (case 2 compared with cases 1 and 3).

In case 2 the heuristics also increased the "non-match category 1" time but the effect was minor because only two out of thirty reallocated time intervals (3 min out of 91 min) belonged to that category. According to heuristics in scenario 2, 3 and 4, the undetected time is divided evenly between the two locations before and after the out of coverage period. If the worker disappeared and reappeared in the same location, this did not result in inaccuracy with this data set. However, if the two locations were different some inaccuracy resulted. Case 1 and 3 did not experience additional inaccuracy due to heuristics and we assume it was because of the denser gateway placement compared to case 2.

Table 9 presents the workers' coverage ratios before and after heuristics at worker level in each of the three projects. The heuristics increased coverage ratios substantially being finally around 8–11% lower than the expected maximum coverage ratios (100% for case 1, and 88% for cases 2 and 3). Heuristics were particularly effective in increasing coverage in cases 2 and 3, in which the gateway density was remarkably lower than in case 1, thereby leaving higher possibilities for areas in which a worker cannot be detected.

3.7. Uninterrupted presence analysis

With improved coverage, it is possible to evaluate the share of uninterrupted presence (research question 3). Presence in a work location is a necessary but not sufficient precondition for value-added work, so we can assume that when the share of time in work locations goes up, also the share of value-adding time increases. In addition, it is reasonable to assume that the worker needs to stay in the work location for some time in order to add value (rather than just briefly visit a location). Therefore, although the proposed system cannot see if value was added in a location, we can estimate a useful metric that is correlated with true value-adding time by looking at uninterrupted presence in

**Table 6**  
Workers' overall coverage ratios in three case projects compared with that of the researcher.

	Detected time (sum in minutes) (1)	Total operational time (sum in minutes) (2)	Workers' coverage ratio (3) = (1)/(2)	Researcher's coverage ratio
Case 1. Plumbing renovation	66,072	98,191	67.3%	72.1%
Case 2. Office open space renovation	47,242	154,482	30.6%	45.1%
Case 3. Apartment building	60,818	121,976	49.9%	88.8%

**Table 7**  
Scenarios to identify status of undetected workers.

Time interval	Gateway (location)	Scenarios
Time 1	Exit gateway	Off-site time
Time 2	Undetected	
Time 3	Exit gateway	
Time 1	Exit gateway	On-site time
Time 2	Undetected	
Time 3	Non-exit gateway	
Time 1	Non-exit gateway	On-site time
Time 2	Undetected	
Time 3	Exit gateway	
Time 1	Non-exit gateway	On-site time
Time 2	Undetected	
Time 3	Non-exit gateway	

locations. Different tasks have different setup times [41]; thus, the length of time a worker needs to be present in the same work location before he/she could possibly add value can differ between tasks. In this research, we did not consider task differences but used different overall threshold times to see how they would impact the share of uninterrupted presence.

Table 10 shows the share of uninterrupted presence (the presence index) at threshold values 0, 1, 5 and 10 min in each case study at a project level. The threshold time is the number of minutes the worker needs to stay in a work location before the time interval is included in the calculation. The presence index was calculated both including the heuristics and without the heuristics. From the table, it is evident that all three case studies have the same pattern: a sharp drop of presence index from 1 to 5 min and less of a drop from 5 to 10 min. This indicates that many of the tracking time intervals are between 1 and 5 min. It can be argued that most of them are non-value adding, since it is difficult to imagine a task where value can be created in five minutes other than minor punch list work or site supervision. Site supervisors and foremen were excluded from this analysis because we assumed that, in contrast with tradesmen, they can create value by merely visiting a location briefly. As expected, the heuristics increased the presence index most in projects with a sparser gateway placement (cases 2 and 3). Presence indexes at the 10 min threshold value were the highest in the apartment building project (case 3) and lowest in the office renovation project (case 2).

The impact of heuristics was highest at lower threshold values which could be because most of the time heuristics fill in the blanks of very short time periods. We decided to investigate this further to

**Table 8**  
The researchers' coverage ratios before and after heuristics (all numbers in minutes except coverage ratios).

Project	Before/after heuristics	Total matched time	Total time of "non-match" category 1 (Accuracy)	Total time of "non-match" category 2 (Flickering)	Total time of "non-match" category 3 (Coverage)	Coverage ratio
Case 1. Plumbing renovation	Before heuristics	52	11	4	27	71.2%
	After heuristics	71	9	4	10	89.3%
Case 2. Office open space renovation	Before heuristics	37	4	0.02	50	45.1%
	After heuristics	55	7	0.02	29	68.1%
Case 3. Apartment building	Before heuristics	54	8	3	8	88.8%
	After heuristics	56	8	3	6	91.8%

**Table 9**  
The workers' coverage ratios before and after heuristics.

Project	Before or after heuristics	Coverage ratio	Daily detected time (minutes)	Total time of the day (minutes)
Case 1	Before	67.3%	66,072	98,191
	After	89.5%	87,886	
Case 2	Before	30.6%	47,242	154,482
	After	77.5%	119,658	
Case 3	Before	49.9%	60,818	121,976
	After	80.1%	98,666	

evaluate the impact of heuristics on the validity of presence index. It turned out that in case 1 there were very few long time intervals where heuristics came into play and most of the time heuristics were needed to fill in the gaps of very short 0–5 min time intervals when the worker was not detected (Table 11). We argue that this is a valid increase of presence index because if the gaps were not filled in, the threshold timer would reset every time the worker went undetected. In the complex indoor environment, these small gaps could not be prevented even in the project with densest gateway placement strategy. However, cases 2 and 3 had a higher amount of time intervals that were over 20 min and thus were considered present even though the system did not detect the workers. This finding guides our proposed gateway placement strategy.

#### 4. Discussion

##### 4.1. System feasibility, generalizability, limitations and application constraints

We implemented the proposed system on three construction sites during indoor construction phase. Construction environment in the cases was relatively stable because the locations stayed the same, for example interior walls were not installed during the process. In all case studies we were able to complete the tests and gained data that was useful for analysis. In addition, the collected data could be used for real-time production control purposes, such as locating people, materials or equipment but these use cases were not in the scope of this paper. From data point of view, the use of the system for these purposes is feasible in real construction projects.

Installation costs of the proposed setup are quite low. The gateway hardware required for each location was Raspberry Pi with an approximate cost of 55 EUR/gateway. The beacons were BLE beacons

**Table 10**  
Presence indexes at work with different threshold values for each case (time in minutes; excluding data of site managers).

Case study project	Tracking period (weekends excluded)	Number of tracked workers	Threshold minutes	Workplace accumulated time (1)	Total time detected (2)	Presence index at work locations (3) = (1)/(2)	Presence index at work locations without heuristics
Case 1. Plumbing renovation	From September 1 to October 13, 2017	10	0	59,009	87,793	67.2%	53.0%
			1	55,502		63.2%	50.1%
			5	36,694		41.8%	33.2%
			10	26,566		30.3%	25.1%
Case 2. Office open space renovation	From September 21 to November 30, 2017	8	0	33,947	93,045	36.5%	18.2%
			1	33,511		36.0%	18.2%
			5	27,322		29.4%	13.7%
			10	22,786		24.5%	10.8%
Case 3. Apartment building	From October 18, 2017 to January 31, 2018	11	0	65,696	121,976	53.9%	30.5%
			1	64,773		53.1%	30.3%
			5	50,411		41.3%	22.2%
			10	43,284		35.5%	19.8%

which can be bought individually for 4 EUR/beacon. Therefore the hardware costs for case studies were 1325 EUR for case 1, 1207 EUR for case 2, 594 EUR for case 3. More important than the hardware costs are the costs associated with installation and maintenance of the system. These were found to be quite modest in our cases. Each case required half a day for investigating the site conditions and installing the gateways based on power availability. After that the gateways were named based on their location in the floorplan and registered in the system. This task took a few hours. Data were monitored daily off-site using the web user interface to see possibly disconnected gateways and the sites were visited biweekly to make sure that the gateways were still in the correct location and plugged in. Thus, the maintenance requirements of the system were also quite limited, 1–2 h per week of construction. However, the projects did not have drastically changing site conditions, for example building of interior walls, which would likely necessitate additional gateways and changing the locations of existing gateways. Additionally, the number of gateways installed in cases were quite similar (10–23) and in a larger project, the setup and maintenance times would roughly increase linearly as a function of gateways. Beacon addition was quite simple, requiring the MAC address of the beacon and could be done in a few minutes for each beacon. To simplify this operation, each beacon had a QR code which showed the MAC address. Therefore, to achieve the functionality proposed in the paper, the hardware, installation and maintenance costs are quite low, on the order of one day for the beginning setup and a few hours per week for maintenance for similar case studies. The proposed system would generalize construction projects in the indoor construction phase where power and connectivity can be arranged.

Key limitation of the prototype system was that Raspberry Pi's require power and connectivity for each device. Connectivity issues could be solved by just adding a 4G dongle to each Raspberry Pi and one of the case studies had a wireless network installed in the job site. The availability of power limited the number of locations where they could be installed, because temporary power was not available throughout the buildings. Using a power bank or battery would not be feasible due to high maintenance requirement. This impacted the locations that could be tracked. In all projects, entrances and exits to each floor had

temporary power, which is probably true for most construction projects because temporary power is typically connected through stairways. The availability of power resulted in differences between the case studies. Sparser gateway placement strategies of cases 2 and 3 resulted in lower coverage of the system which had to be resolved through heuristics. The need for heuristics was much lower in case 1 where power could be organized to most of the apartments where work was happening. In future hardware development, these limitations could be addressed by developing a lightweight gateway that only has the minimum functionality required by the system. Such a light gateway could be powered by a battery for the entire duration of the indoor construction phase, in contrast with Raspberry Pi which is essentially a mini-computer with much more functionality than is required in this simple use case. Connectivity was not a big issue in these projects but it could be enhanced by having the gateways function as a mesh network [42].

4.2. Data coverage and accuracy

Park et al. [11] examined the various wireless solutions for tracking and found that Bluetooth technology stands minimal false negative alerts within a range of 18.3 m. In our cases, system coverage was rather low, particularly in the open space renovation project with low gateway density and in the plumbing renovation project where gateways were placed in apartments and there could be interference in the radio signals from the walls. The findings indicate that in actual construction jobsites, the raw tracking dataset does not return a very satisfactory coverage. Moreover, earlier research has reported problems with data flickering (i.e., [38–40]); however, in our dataset the amount of data flickering and incorrectly reported locations were rather low. Thus, it was necessary to develop heuristics in the tracking system in order to enhance coverage. After applying simple heuristic rules, the coverage ratios improved remarkably in all case studies without causing significant loss of accuracy. In summary, this shows that even if raw system data in a real project environment may have low quality, simple heuristic rules—which consider gateways' type, such as exit and non-exit location in our cases—can be applied to remarkably improve the data coverage. Because coverage could be improved through

**Table 11**  
Distribution of counts and percent of time intervals the heuristics applied in all cases.

Case study project	Time intervals 0–5 min (counts/%)	Time intervals 5–10 min (counts/%)	Time intervals 10–15 min (counts/%)	Time intervals 15–20 min (counts/%)	Time intervals 20+ minutes (counts/%)
Case 1. Plumbing renovation	15,891	1379	543	280	521
	84%	7%	3%	2%	3%
Case 2. Office open space renovation	4176	811	435	263	638
	64%	12%	7%	4%	13%
Case 3. Apartment building	5743	1006	475	293	979
	64%	12%	6%	3%	12%

heuristics without sacrificing accuracy, it was then possible to use the data to conduct uninterrupted presence analysis.

#### 4.3. Uninterrupted presence analysis

The system allows us to detect the presence of workers in work locations. We cannot know whether the workers were engaged in value-adding work when they were present in the work location but we know that if the workers briefly visit a work location or if the workers are in non-work locations, they are not doing installation work. In other words, presence is a necessary but not a sufficient condition for value-added time. Therefore, although we cannot claim that we are accurately calculating the share of value added time, we can provide a metric that is easy to calculate and we assume it is correlated with real value-added time and thus productivity. If the workers spend longer time periods in work locations and if we assume that the share of value-added time in work locations stays constant, increased share of longer duration presence means higher value-added time.

In order to estimate metric presence index of project resources, we calculated the percentage of time that workers spent on workplaces using different thresholds of set-up time. Josephson and Saukkoriipi [43] found that waiting time constituted 23% of the working time as one kind of waste and indicated that approximately 49% was directly value-adding work in construction. Furthermore, Diekmann et al. [44] showed that the value-adding constituted approximately 32% of the time in one construction project. Our findings of 25%–36% workplace presence time with a 10-minute value-adding time threshold are in line with these results. Thus, we argue that our new metric using real-time BLE tracking technology combined with heuristics and threshold analysis can provide a real-time estimate on how much waste there is in the construction process.

Despite the promising results, several limitations in data quality need to be addressed when analyzing the presence index. First, the gateway placement strategy may create overlapping or blank coverage areas that influence the accuracy of data and, thus, uninterrupted presence analysis. Our findings indicate that gateways should optimally be placed in every work location. In apartment buildings, flickering between locations was not a major problem in our study although the gateway spheres of influence were overlapping. The concrete floors and walls were enough to dampen the signal between apartments. Therefore in apartment buildings, the gateways should be placed in each apartment where work is happening, as well as at every exit location in the building. This would minimize the need for heuristic use and increase coverage. In large open areas, such as case 2, more gateways should be installed to increase coverage. Placing gateways very close to each other would likely increase the magnitude of flickering problem. We propose that the gateways in open areas should be installed roughly at 30 m intervals based on beacon range of roughly 15 m and a small overlap required to eliminate areas of no coverage. In summary, we propose the following four guidelines for gateway placement: (1) at each exit location; (2) in any work location enclosed by concrete walls, such as apartments (e.g. cases 1 and 3); (3) in locations where it is possible to access other floors (stairwells, elevators); (4) in open spaces at least every 30 m. Using these guidelines, in our case 1, we would have needed 11 more gateways (one for each apartment and stairwell location without a gateway). In case 2, the guidelines would lead to two additional gateways for all floors except the second floor which had 5 gateways already (total of 12 additional gateways). In case 3, each apartment should have had its own dedicated gateway, in addition to the stairwell gateway (a total of 33 additional gateways).

Second, the results excluded the tracking data for site managers. This decision was taken because value-adding work for a site manager should be defined differently than that for normal workers. Site managers usually walk around the jobsite visiting several work locations briefly and spend most of their time in the office, which is defined as an exit location that did not add to work location presence index in our

analysis. In future analysis, we will also conduct value-adding data analysis for site managers, for example, to see how many times site managers walk around in non-exit work locations and how much time they spend in the office.

Our data validation was mostly based on the analysis of researchers' movement data and not real worker data. The threshold times could be better calibrated by comparing actual movements and locations to recordings with different threshold times. In future research, the automated tracking should be compared with ground-truth data of observed worker movements (e.g., [43]) to identify task-based differences and what is actually happening when the workers are not in a work location. We envision a hierarchical system where the construction project can easily implement the measurement of presence index of workers with inexpensive installation. It is then possible to get deeper and evaluate real value-adding time and even productivity by implementing other technologies, such as vision-based approaches (e.g. [34]) or integrated approaches based on posture (e.g. [31]) or accelerometer data (e.g. [35]). These more detailed approaches need to be tailored to each work type and require extensive training of the algorithms, while our proposed presence index metric gives a useful generic measure of the efficiency of the site and of each contractor. In our future research, we are looking to augment the indoor positioning based data with accelerometer data and with video data acquired with helmet cameras. However, this cannot be easily done for all the workers.

In terms of uninterrupted presence analysis, the patterns of data for different case studies were notably different. For example, in the plumbing renovation project (case 1), the presence index with a threshold time of 0 min was 67.2% (the total amount of time workers were in work locations); however, it dropped to 30.3% when the threshold time was increased from 0 to 10 min, thereby indicating that although workers were present in work locations most of their time, there was a lot of movement between different apartments. Based on validation results, these were actual movements because the amount of flickering was rather low in that case study. In the office project, the workplace presence index with a 0-minute threshold was merely 36.5%, thereby indicating that the workers spent a lot of time in the office, storage, or entrance areas but it dropped to just 24.5% when the threshold time increased to 10 min. It is likely that with sparse gateway placement, many short distance movements cannot be detected and the actual reduction would be higher if the optimum gateway placement strategy had been followed.

#### 4.4. Contribution to knowledge

The research contributes a new scalable way of measuring a worker's presence in work locations using a gateway and Bluetooth low energy beacon solution. Continuous presence in a work location is a necessary but not sufficient prerequisite to adding value to the building and it can be reliably calculated in real-time with an inexpensive, low maintenance system. It seems intuitive that this easily calculable metric is correlated with value-adding time and productivity.

Other approaches related to our method include work sampling, which classifies workers' activities as one of three types: productive, semi-productive and non-productive [45]. Normally work sampling has been done based on direct observation of construction workers [34,45] which is costly and not scalable. Related technology-based approaches can be divided to image-based and sensor-based. For example, Luo et al. [34], developed a taxonomy method based on site surveillance videos to address more efficient work sampling in 16 classes of activities. Work sampling can also be implemented automatically by using posture recognition with accelerometer [e.g. 35]. These types of approaches require extensive training data sets for each class of activity and thus cannot be easily implemented as an overall approach in all projects. We think that our rough but easy to deploy metric, together with more detailed approaches tailored for each work type, could be a powerful and complementary combination. Our metric gives an estimate of the

overall efficiency of the work site. It can be used for evaluating the functioning of site supervision, equipment handling, material logistics and support processes and identify potential problems in real time. The more detailed approaches aim at accurate productivity calculations for individual tasks. Both approaches have an important role to play in automated production control.

In summary, our method contributes a new lighter-weight, holistic and passive automated system which gives an indication of worker's presence in work locations. The data from these three case studies show that this share is very low and raises intriguing future research questions that will be addressed in future research. Why is there so much movement on construction sites? Why are the workers not able to spend more time in the work locations? Are the workers present in the correct locations? Answering these questions requires more context data and combinations of different data collection technologies.

#### 4.5. Comparison to other digital approaches

Another way to collect information from tasks of the workers is QR code scanning which has been proposed by Raj et al. [46], for building navigation system for closed building using smartphones where they demonstrated advantages of QR code with low maintenance requirement and infrastructure cost. Similarly, a lot of mobile applications exist, where the worker can enter where they started and finished work [9]. However, these applications rely on input by the worker. It is possible that the start and finish times are accurately entered. However, wasted effort seen as movement would not be observed in these systems because the workers generally see movement as part of their value-adding work. This is analogous to the survey results (e.g. [6,12]), where it has been shown that workers do not understand the concept of waste and thus the survey results are different from objective observations.

#### 4.6. Managerial implications

Share of time workers are able to spend in work locations has important managerial implications. Waste cannot normally be influenced by any single worker or actor because it is by nature a problem with flow between value-adding activities [6,17]. Therefore, decreasing the waste in the project is part of the coordination responsibility of the project. There has not been a good way to measure how much time is being wasted on each project and which factors impact the waste. Presence in work locations for extended time periods can offer a simple metric that can work as a proxy for waste. The management can evaluate the amount of worksite presence before and after lean or digital interventions. For example, material logistics has been shown to be a major contributor to waste [16]. If the project implements just-in-time logistics, it could be evaluated how much it would impact the presence of workers in work locations. Similarly, although a lot of digital tools have been proposed in construction, the construction industry still suffers from low productivity. New digital tools should pass the test whether they increase the share of time workers can spend in work locations or not. In addition, real-time evaluation is of importance. If project problems can be seen in real time by looking at the share of time workers spend in work locations, this could highlight issues that are unknown to management. Our assumption, which will be validated in future research, is that problems of flow can be seen as movement. Problems lead to a requirement to find new work locations or to look for help which should immediately be reflected in lower uninterrupted presence in work locations.

## 5. Conclusion

This research has illustrated how a real-time tracking system based on a BLE technology can be implemented on different types of indoor construction projects, more specifically in apartment plumbing renovation, residential building, and office building. The data accuracy

and coverage of the tracking system were tested, developed, and discussed. Heuristics based on gateway location were developed to improve system coverage and data accuracy. When exploring the presence in work locations for the tracked workers in the projects, several threshold value times were introduced to identify uninterrupted presence which would be a necessary but not sufficient condition for value added work. Through this method, presence indices at the project level can be calculated from the system data. Presence indices in the case projects ranged between 25% and 36% (at a threshold value of 10 min), which matches previous studies in which value-added time was evaluated and the data were collected manually. Therefore we suggest that uninterrupted presence is strongly correlated with value-added time.

The study suggests that a real-time tracking system based on BLE technology can be applied in construction projects for real-time tracking purposes and uninterrupted presence analysis. However, appropriate gateway placement strategy and heuristics to improve data accuracy and coverage should be applied if managers wish to obtain actual benefits from the system. In particular, gateways should be placed at roughly 30 m intervals if there are no areas enclosed by concrete walls or in each work location separated by concrete walls, as well as all exits and locations where it is possible to transfer between floors. Being able to evaluate workers' presence in work locations in real-time and with a scalable solution presents a significant academic and practical contribution. From the research perspective, it becomes possible to measure the impact of construction management or digitalization interventions on long term presence of the workers in work locations. From a practical standpoint, presence information can be used by managers to compare efficiency in different projects. For project management, the daily measurement of presence in work locations could identify problems that are currently unknown to the management or highlight the impact of problems, for example, to address productivity impacts of delays. Further research is needed on the real value of the tracking data in projects, both for managers and workers. This would require integration of the tracking data with other information, for example, from BIM or a production planning system. In addition, more investigations are also required with regard to optimal gateway placements in different project types. We also propose to integrate the calculation of presence in work locations with more detailed automated work sampling methods such as accelerometer or posture detection, to get a deeper productivity analysis of those activities where algorithms have been trained to recognize value-adding time. These more detailed methods could be targeted to those tasks and projects which consistently show low presence indices.

## Acknowledgements

This work was supported by Tekes (Finnish funding agency for technology and innovation) grant number 2819/31/2016.

## References

- [1] J. Bakhshi, V. Ireland, A. Gorod, Clarifying the project complexity construct: past, present and future, *Int. J. Proj. Manag.* 34 (7) (2016) 1199–1213, <https://doi.org/10.1016/j.ijproman.2016.06.002>.
- [2] A. Mills, A systematic approach to risk management for construction, *Struct. Surv.* 19 (5) (2001) 245–252, <https://doi.org/10.1108/02630800110412615>.
- [3] L.A. Vidal, F. Marle, Understanding project complexity: implications on project management, *Kybernetes* 37 (8) (2008) 1094–1110, <https://doi.org/10.1108/03684920810884928>.
- [4] H.R. Thomas, M.J. Horman, U.E.L. de Souza, I. Zaviški, Reducing variability to improve performance as a lean construction principle, *J. Constr. Eng. Manag.* 128 (2) (2002) 144–154, [https://doi.org/10.1061/\(ASCE\)0733-9364\(2002\)128:2\(144\)](https://doi.org/10.1061/(ASCE)0733-9364(2002)128:2(144)).
- [5] H.G. Ballard, The Last Planner System of Production Control, Doctoral dissertation University of Birmingham, 2000, <http://theses.bham.ac.uk/4789/1/Ballard00PhD.pdf> (May, 2000).
- [6] O. Seppänen, G. Ballard, S. Pesonen, The combination of last planner system and location-based management system, *Lean Constr. J.* 6 (1) (2010) 43–54 [https://www.leanconstruction.org/media/docs/lcj/2010/LCJ\\_10\\_014.pdf](https://www.leanconstruction.org/media/docs/lcj/2010/LCJ_10_014.pdf).
- [7] O. Seppänen, J. Evinger, C. Mouflard, Effects of the location-based management system on production rates and productivity, *Constr. Manag. Econ.* 32 (6) (2014)

- 608–624, <https://doi.org/10.1080/01446193.2013.853881>.
- [8] T. Hegazy, W. Menesi, Critical path segments scheduling technique, *J. Constr. Eng. Manag.* 136 (10) (2010) 1078–1085, [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000212](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000212).
- [9] A. Costin, N. Pradhananga, J. Teizer, Leveraging passive RFID technology for construction resource field mobility and status monitoring in a high-rise renovation project, *Autom. Constr.* 24 (2012) 1–15, <https://doi.org/10.1016/j.autcon.2012.02.015>.
- [10] P.M. Goodrum, M.A. McLaren, A. Durfee, The application of active radio frequency identification technology for tool tracking on construction job sites, *Autom. Constr.* 15 (3) (2006) 292–302, <https://doi.org/10.1016/j.autcon.2005.06.004>.
- [11] J. Park, E. Marks, Y.K. Cho, W. Suryanto, Performance test of wireless technologies for personnel and equipment proximity sensing in work zones, *J. Constr. Eng. Manag.* 142 (1) (2016) 04015049, [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001031](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001031).
- [12] P. Lin, Q. Li, Q. Fan, X. Gao, Real-time monitoring system for workers' behavior analysis on a large-dam construction site, *Int. J. Distrib. Sens. Netw.* 9 (10) (2013) 509423, <https://doi.org/10.1155/2013/509423>.
- [13] H. Olivieri, O. Seppänen, A. Peltokorpi, Real-time tracking of production control: requirements and solutions, in: K. Walsh, R. Sacks, I. Brilakis (Eds.), 25th Annual Conference of the International Group for Lean Construction, Heraklion, Greece, 9–12 Jul 2017, 2017, pp. 671–678, <https://doi.org/10.24928/2017/0177>.
- [14] A. Vasenev, T. Hartmann, A.G. Doree, A distributed data collection and management framework for tracking construction operations, *Adv. Eng. Inform.* 28 (2) (2014) 127–137, <https://doi.org/10.1016/j.aei.2014.01.003>.
- [15] T. Ohno, *Toyota Production System: Beyond Large-scale Production*, 1 edition, Productivity Press, 1988 (1 Mar. 1988). (ISBN-13: 978-0915299140).
- [16] H. Ismail, Z.M. Yusof, Perceptions towards non-value-adding activities during the construction process, in: S. Kamaruzzaman, A. Ali, N. Azmi, S. Lin (Eds.), The 4th International Building Control Conference 2016, vol. 66, 2016, p. 00015 Kuala Lumpur, Malaysia, 7–8 March 2016 <https://doi.org/10.1051/mateconf/20166600015>.
- [17] B.T. Kalsaas, M. Gundersen, T.O. Berge, To measure workflow and waste. A concept for continuous improvement, in: B.T. Kalsaas, L. Koskela, T.A. Smith (Eds.), Proceedings of the 22nd Annual Conference of the International Group for Lean Construction, IGLC & Akademika forlag, Oslo, Norway, 978-1-5108-0723-5, 2014, pp. 835–846.
- [18] A.R. Lapinski, M.J. Horman, D.R. Riley, Lean processes for sustainable project delivery, *J. Constr. Eng. Manag.* 132 (10) (2006) 1083–1091, [https://doi.org/10.1061/\(ASCE\)0733-9364\(2006\)132:10\(1083\)](https://doi.org/10.1061/(ASCE)0733-9364(2006)132:10(1083)).
- [19] M. Loosemore, Improving construction productivity: a subcontractor's perspective, *Eng. Constr. Archit. Manag.* 21 (3) (2014) 245–260, <https://doi.org/10.1108/ECAM-05-2013-0043>.
- [20] M.M.M. Teo, M. Loosemore, A theory of waste behavior in the construction industry, *Constr. Manag. Econ.* 19 (7) (2001) 741–751, <https://doi.org/10.1080/01446190110067037>.
- [21] R. Kenley, O. Seppänen, Location-based Management of Construction Projects: Part of a new typology for project scheduling methodologies, in: M.D. Rossetti, R.R. Hill, B. Johansson, A. Dunkin, R.G. Ingalls (Eds.), Simulation Conference, Proceedings of the 2009 Winter, 2009, pp. 2563–2570. Austin, Texas, the USA, 13–16 December, 2009.
- [22] R. Sacks, R. Navon, A. Shapira, I. Brodetsky, Monitoring construction equipment for automated project performance control, National Institute of Standards and Technology Special Publication, 2003, pp. 161–166 <http://www.irbnet.de/daten/iconda/CIB12939.pdf>.
- [23] J. Dong, Y. Xiao, M. Noreikis, Z. Ou, A. Ylä-Jääski, imoon: using smartphones for image-based indoor navigation, Proceedings of the 13th Association for Computing Machinery Conference on Embedded Networked Sensor Systems, 2015, pp. 85–97 Seoul, South Korea, November 01.04, 2015 <https://doi.org/10.1145/2809695.2809722>.
- [24] H. Liu, H. Darabi, P. Banerjee, J. Liu, Survey of wireless indoor positioning techniques and systems, *IEEE Trans. Syst. Man Cybern. Part C Appl. Rev.* 37 (2007) 1067–1080, <https://doi.org/10.1109/TSMCC.2007.905750>.
- [25] J. Park, K. Kim, Y.K. Cho, Framework of automated construction-safety monitoring using cloud-enabled BIM and BLE mobile tracking sensors, *J. Constr. Eng. Manag.* 143 (2) (2017) 05016019, [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001223](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001223) (February 2017).
- [26] J. Zhao, H. Olivieri, O. Seppänen, A. Peltokorpi, B. Badihi, P. Lundström, Data analysis on applying real time tracking in production control of construction, *Industrial Engineering and Engineering Management (IEEM)*, 2017 IEEE International Conference on, 2017, pp. 573–577 Singapore, 10–13 December <https://doi.org/10.1109/IEEM.2017.8289956>.
- [27] A. Alarifi, A. Al-Salman, M. Alsaleh, A. Alnafessah, S. Al-Hadhrami, M.A. Al-Ammar, H.S. Al-Khalifa, Ultra-wideband indoor positioning technologies: analysis and recent advances, *Sensors* 201616 (5) (2016) 707, <https://doi.org/10.3390/s16050707>.
- [28] Y. Gu, A. Lo, I. Niemegeers, A survey of indoor positioning systems for wireless personal networks, *IEEE Commun. Surv. Tutorials* 11 (2009) 13–32, <https://doi.org/10.1109/SURV.2009.090103>.
- [29] Z. Deng, Y. Yu, X. Yuan, N. Wan, L. Yang, Situation and development tendency of indoor positioning, *China Commun.* 10 (3) (2013) 42–55, <https://doi.org/10.1109/CC.2013.6488829>.
- [30] K. Benkic, M. Malajner, P. Planinsic, Z. Cucej, Using RSSI value for distance estimation in wireless sensor networks based on ZigBee, in: G. Rozinaj, J. Cepko, P. Truchly, J. Vrabec, J. Vojtko (Eds.), Systems, Signals and Image Processing, 2008. 15th International Conference on Systems, Signals and Image Processing, 2008, June, pp. 303–306 Bratislava, Slovakia, 25–28 June 2008 <https://doi.org/10.1109/IWSSIP.2008.4604427>.
- [31] T. Cheng, J. Teizer, G.C. Migliaccio, U.C. Gatti, Automated task-level activity analysis through fusion of real time location sensors and worker's thoracic posture data, *Autom. Constr.* 29 (2013) 24–39, <https://doi.org/10.1016/j.autcon.2012.08.003>.
- [32] H. Jiang, P. Lin, M. Qiang, Q. Fan, A labor consumption measurement system based on real-time tracking technology for dam construction site, *Autom. Constr.* 52 (2015) 1–15, <https://doi.org/10.1016/j.autcon.2015.02.004>.
- [33] J. Yang, M.W. Park, P.A. Vela, M. Golparvar-Fard, Construction performance monitoring via still images, time-lapse photos, and video streams: now, tomorrow, and the future, *Adv. Eng. Inform.* 29 (2) (2015) 211–224, <https://doi.org/10.1016/j.aei.2015.01.011>.
- [34] X. Luo, H. Li, D. Cao, Y. Yu, X. Yang, T. Huang, Towards efficient and objective work sampling: recognizing workers' activities in site surveillance videos with two-stream convolutional networks, *Autom. Constr.* 94 (2018) 360–370, <https://doi.org/10.1016/j.autcon.2018.07.011>.
- [35] J. Ryu, J. Seo, H. Jebelli, S. Lee, Automated action recognition using an accelerometer-embedded wristband-type activity tracker, *J. Constr. Eng. Manag.* 145 (1) (2018) 04018114, [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001579](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001579).
- [36] K. Peffers, T. Tuunanen, M.A. Rothenberger, S. Chatterjee, A design science research methodology for information systems research, *J. Manag. Inf. Syst.* 24 (3) (2007) 45–77, <https://doi.org/10.2753/MIS0742-1222240302>.
- [37] R.K. Yin, *Case Study Research: Design and Methods*, Sage Publications, Beverly Hills, 0-7619-2552-X, 2013.
- [38] I. Barandiaran, C. Paloc, M. Graña, Real-time optical markerless tracking for augmented reality applications, *J. Real-Time Image Proc.* 5 (2) (2010) 129–138, <https://doi.org/10.1007/s11554-009-0140-2>.
- [39] S.W. Leung, S. Mak, B.L. Lee, Using a real-time integrated communication system to monitor the progress and quality of construction works, *Autom. Constr.* 17 (6) (2008) 749–757, <https://doi.org/10.1016/j.autcon.2008.02.003>.
- [40] C. Stauffer, W.E.L. Grimson, Learning patterns of activity using real-time tracking, *IEEE Trans. Pattern Anal. Mach. Intell.* 22 (8) (2000) 747–757, <https://doi.org/10.1109/34.868677>.
- [41] A. Allahverdi, H.M. Soroush, The significance of reducing setup times/setup costs, *Eur. J. Oper. Res.* 187 (3) (2008) 978–984, <https://doi.org/10.1016/j.ejor.2006.09.010>.
- [42] B.K. Gupta, S. Patnaik, M.K. Mallick, A.K. Nayak, Dynamic routing algorithm in wireless mesh network, *Int. J. Grid Util. Comput.* 8 (1) (2017) 53–60, <https://doi.org/10.1504/IJGUC.2017.082144>.
- [43] P.E. Josephson, L. Saukkoripii, *Waste in Construction Projects: Call for a New Approach*, Chalmers University of Technology, 978-91-976181-7-5, 2007.
- [44] J.E. Diekmann, M. Krewedl, J. Balonick, T. Stewart, S. Won, Application of lean manufacturing principles to construction, *Lean Constr. J.* 2 (2) (2005) 2005. October 2005. [https://www.leanconstruction.org/media/docs/lcj/V2\\_N2/LCJ\\_05\\_011.pdf](https://www.leanconstruction.org/media/docs/lcj/V2_N2/LCJ_05_011.pdf).
- [45] S.P. Dozzi, S.M. AbouRizk, *Productivity in Construction*, Institute for Research in Construction, National Research Council, Ottawa, ON, Canada, 0-662-21134-0, 1993.
- [46] C.R. Raj, S. Tolety, C. Immaculate, QR code based navigation system for closed building using smart phones, 2013 International Mutli-Conference on Automation, Computing, Communication, Control and Compressed Sensing, IEEE, Kottayam, India, 2013, pp. 641–644, <https://doi.org/10.1109/iMac4s.2013.6526488>.