Department of Civil Engineering

Production Control Using Real-Time Monitoring in Construction

Jianyu Zhao

Aalto University

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Jianyu Zhao

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Aalto University
School of Engineering
Department of Civil Engineering

Supervising professors
Professor Olli Seppänen, Aalto University, Finland
Professor Antti Peltokorpi, Aalto University, Finland

Thesis advisor
Professor Hylton Olivieri, IPT - Institute for Technological Research, Brazil

Preliminary examiners
Professor Martin Rudberg, Linköping University, Sweden
Professor Kalle Kähkönen, Tampere University, Finland

Opponent
Professor Jochen Teizer, Technical University of Denmark, Denmark

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Abstract

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

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Abstract

Construction projects are known to be full of complexity because they interconnect high quantities of elements, including labor, tasks, and components. The complexity often results in risks such as poor work productivity and interruptions of production workflows, which further leads to unexpected and wasteful activities on-site. A well-functional production control system in construction is important in enabling smooth workflows with minimal waste and variability.

Waste measurement is difficult and complex through conventional measurement techniques in construction. For instance, notable waste happens in labor movement and material flows, but the challenges of measuring the waste are still hard to address in construction. Therefore, it is of great benefit to develop a scalable and automated system that measures wasteful events and improves site operations in construction. If an automated real-time monitoring system in construction can be implemented with ease and satisfactory coverage and accuracy, it is then possible to assess the movement of labor and materials on-site. Next, the analyses of movement can be conducted to reflect upon the magnitude of variability at the project and task levels, which helps waste elimination and improvement of production control.

The overall objective of the research is to improve production control in construction by estimating workers' presence on-site at the project and task levels to support task progress monitoring and to assess task workflow and material management practice. First, the thesis demonstrates how the proposed real-time monitoring system can be implemented in different types of indoor construction projects. The data accuracy and coverage of the system were evaluated, and heuristics were also proposed to improve the system's coverage. With this method, presence indices were calculated, matching previous studies in which value-added time was evaluated and the data were collected manually. Second, the thesis illustrates how the system can be installed to detect task start and finish times, measuring and validating task progress data automatically. Third, the thesis also shows how the proposed system could be applied for the automated detection and analyses of time-matching level of materials and workers based on their uninterrupted presence, which can be used to evaluate the kitting material solution practice.

From a research perspective, this study makes it possible to measure the impact of construction management or digitalization interventions on the long-term presence of workers and materials in work locations. From a practical standpoint, managers can use the suggested presence information 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, e.g., the productivity impacts of delays.

Keywords Operations management in construction, real-time monitoring, production control, task progress, material and labor monitoring, waste, variability, uninterrupted presence, data analysis

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It has been such a journey! Honestly, I have never thought about my feelings when I finally get to write something in this section. But today is the day, and I feel delighted, relieved, emotional and a little bit nostalgic. Through this PhD study journey, I had the chance to push my limits, to develop my character, to learn, and to cooperate. I am grateful for all that happened during this journey.

Firstly, I would like to sincerely extend my thanks to my PhD supervisor Prof. Olli Seppänen, who provided me with support, guidance and mentoring. I started my PhD journey with conducting some of his projects at Aalto, during which he supported me with data collection, academic writing, conference presentations, and so on. He is always a quick responder to my requests, while ensuring freedom and rigorousness for my research. I learned extensively from him, not only invaluable knowledge in operations management in construction, but also how to be a qualified researcher as a whole. Thank you, Olli!

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Finally, for anyone who is reading the thesis, I thank you for your interests. It will make my day if my research helps you even a bit.

Helsinki. November 1, 2022

Jianyu Zhao

Acknowledgement

如果母校阿尔托大学允许的话，很荣幸能够在自己的致谢板块用母语中文写写自己这一路博士学习的心路历程和想要感谢的人和事，酸甜苦辣，终归到了一个需要总结的一个节点。

小的时候记得父亲给我说“散文写得不错，长大了如果论文也像这样的文笔就更好了”，没想到快二十年过去了，反过来我正在严肃的学术论文上记录下自己一些感受，何尝又不可以呢。

最想感谢的当然是我的父母。我父亲明年就六十岁了，我想起我爷爷一个甲子的时候我父亲特意安排当年全家人去新疆旅行了一大圈，都在一起。可能我们这一代人更加追求自我吧，我选择了在异国他乡独自完成学业，所以我想感谢他们的理解与支持，陪伴古难全，唯有自己先修身立业吧。感谢我的爷爷奶奶，我知道您们很盼望这个毕业证书，如今这个学位虽迟但到也算欣慰吧。感谢姑妈哥哥，一路走来的加油和守候，有你们真好。感谢所有亲友的挂念，月明终有时，但求游子心。

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最后还要郑重地感谢一下自己，你做到了，这虽然不是起点亦或是终点，但毕竟还算是我们在这个纷繁世界偶尔需要一些仪式感的时候浓墨重彩的一笔。阿图尔·叔本华曾写过人生有如钟摆，摆动于痛苦和无聊之间，得到了就会无聊，未曾得到终究痛苦，所以无聊和痛苦是人生的两种最后成分。感慨于这一句貌似非常悲观的定义，却完美地诠释了我这五年博士之路遇到的各种低谷与泪水，以及为了打破这样的所谓定义而付出的努力。诚然，不奢望这篇博士论文能够带来多么重要的启示和发明，只求到暮年回首时还能记起自己当年的那一份坚持和汗水，编译成此时此刻的白纸黑字。

请把自己当成人生这一部戏的主角，博士也好论文也罢，终究也只是这一段戏中的逗号而非全部。我们有义务对自己的演技负责，想做就去做吧，痛苦也好无聊也罢，但不要让后悔去扰乱了你独一无二的戏路。

以此共勉。

赵健宇
2022年7月31日
芬兰，拉普兰

Contents

List of Abbreviations

API	Application programming interface
BLE	Bluetooth Low Energy
CPM	Critical path method
GPS	Global Positioning System
GUI	Graphical user interface
KPIs	Key performance indicators
LBMS	Location-based management system
LPS	Last Planner system
MAC	Media access control
MQTT	Message Queuing Telemetry Transport
NM	No material
PIs	Presence indices
PPC	Percent plan complete
PPs	Presence-to-plan ratios
PSM	Physiological status monitor
REST	Representational state transfer
RFID	Radio-frequency identification
RSSI	Received signal strength indication
RTLS	Real-time location sensor
TMA	Time matching for any
TMD	Time matching for designated
TPTC	Takt planning and Takt control
UUID	Universally unique identifier
UWB	Ultra-Wideband

List of Publications

This doctoral thesis consists of a summary of the following publications, which are referred to in the text by their numerals. Publications are reproduced with the permission of the publishers.

1. Zhao, Jianyu; Seppänen, Olli; Peltokorpi, Antti; Badihi, Behnam; Olivieri, Hylton. (2019). Real-time resource tracking for analyzing value-adding time in construction. Elsevier. Automation in Construction, 104, 52–65. ISSN: 0926-5805. https://doi.org/10.1016/j.autcon.2019.04.003

2. Zhao, Jianyu; Pikas, Ergo; Seppänen, Olli; Peltokorpi, Antti. (2021). Using real-time indoor resource positioning to track the progress of tasks in construction sites. Frontiers Media S.A. Frontiers in Built Environment: Construction Management, 7, 661166. ISSN: 2297-3362. https://doi.org/10.3389/fbuil.2021.661166

3. Zhao, Jianyu; Zheng, Yuan; Seppänen, Olli; Tetik, Müge; Peltokorpi, Antti. (2021). Using real-time tracking of materials and labor for kit-based logistics management in construction. Frontiers Media S.A. Frontiers in Built Environment: Construction Management, 7, 713976. ISSN: 2297-3362. https://doi.org/10.3389/fbuil.2021.713976

Author's Contribution

Publication 1: Real-time resource tracking for analyzing value-adding time in construction

Jianyu Zhao implemented real-time tracking in the case studies, developed the idea and methods, collected the data, performed system validation on-site, conducted data analyses, and wrote the manuscript with reviews and comments from Olli Seppänen, Antti Peltokorpi, and Hylton Olivieri. The monitored system was coded by Behnam Badihi.

Publication 2: Using real-time indoor resource positioning to track the progress of tasks in construction sites

Jianyu Zhao implemented the real-time tracking in the case study, developed the idea and methods, collected the data, performed system validation on-site, conducted data analyses, and wrote the manuscript with reviews and comments from Olli Seppänen, Antti Peltokorpi, and Ergo Pikas.

Publication 3: Using real-time tracking of materials and labor for kit-based logistics management in construction

Jianyu Zhao implemented the real-time tracking in the case study, performed the system validation, and collected the required data. Jianyu Zhao, together with the coauthor Yuan Zheng, developed the framework and the method. Jianyu Zhao wrote most of the manuscript. The work was reviewed and commented on by Olli Seppänen, Antti Peltokorpi, and Müge Tetik.

1. Introduction

1.1 General contexts

Construction projects consist of many interconnecting elements, including people, components, and tasks [1]. Because of the many interrelated parts during the construction phase, complexity is a common term used when discussing construction projects and their site management. The complexity increases risks related to construction deadlines and cost targets [2] and is likely to cause low work efficiency and disruption of production workflows, often leading to unplanned and wasteful events on-site. Waste is manifested in waiting, rework, unnecessary movement, and handling of materials among work locations [3].

Achieving a smooth workflow with minimal waste can be realized by improving production control systems in construction [4]. Effective production control in construction is imperative to enable reliable workflow and to address the root causes of wasteful events during construction phases.

For an effective production control system, five principles were outlined by Koskela [5] in previous studies:

- The prerequisites of the assignments should be fulfilled to minimize the work under suboptimal conditions.
- It is important to ensure that the assignments are measured and monitored, which decreases the risk of variability to impact flows and tasks. Variability is formally defined as the quality of nonuniformity of a class of entities, whereas flows refer to the transfer of jobs or parts from one station to another [6]. In construction, variability in the flow of work is typically seen in the building process [7].
- The causes of unrealized assignments are assessed and then removed.
- A buffer of unassigned tasks should be maintained in each trade. Buffers could be described as some type of shield against the negative impacts of work disruptions and variability [8].
- The prerequisites of upcoming assignments in look-ahead planning should be actively made ready.

On top of Koskela's view, Ballard [4] added his view where he highlighted the source of variability in construction and the importance of variability in the production system. More specifically, he pointed out that variability must be mitigated, which is often virtually disregarded in the current control system. Variability exists in many ways in the construction industry, including variability in quality, variability in processing times, variability in deliveries, etc. Ballard also argued that variability could not be left uncontrolled since ignorance of variability would lead to even larger variability, which comes with a penalty. Variability impacts some or all of the following [4]: (1) buffering of flows, which increases lead times and work-in-process; (2) lower resource utilization; and (3) lost throughput.

Furthermore, Koskela [5] pointed out that there is relatively high variability due to construction peculiarities. There he presented examples that variability could be reflected upon inherently variable manual labor productivity, the availability of space, external changeable conditions, lacking at the intended start of the work, and errors. Therefore, addressing and understanding workflow variability is important in construction production planning and control.

There is a great amount of variability in construction. A high level of workflow variability of tasks is one of the causes of waste [9]. Santos referred to waste as "everything that is not absolutely essential" and work as "any task that adds value to the product" [10]. Hirano argued that waste could be separated from useful activities [11], so it provides opportunities to divide operations into activities that do or do not add value to the end product [12]. Previous studies attempt to decrease waste by enhancing work structuring and measuring completion of activities [13] since waste measurement is important for causes of interruptions. Still, the data required for production control and task progress monitoring is hard to obtain.

Waste measurement is complex with traditional measurement techniques. For instance, logistics in construction is important, but its performance is difficult to measure, and waste inevitably occurs in material flows [14]. In the context of material flows in the stage of inventory and processing, notable wasteful activities could be found, such as (1) unnecessary handling of material, (2) searching for correct resources, and (3) waiting to use the resource [15], all of which lead to wasted efforts concerning material mishandling. Furthermore, incorrectly placed materials result in waste, which causes rework and delays [16], hindering labor performance and task progress. Workflows can also be potentially blocked by the spaces used to store materials [17]. Therefore, it is important to measure waste to enhance material flows, for instance, by assuring the use of materials at the right time and at the correct work location.

Furthermore, notable waste also occurs in labor movement, but challenges of measuring it accurately still prevail in construction. In the context of workers' waste, conventional approaches to detecting and analyzing workers' movement and waiting in construction often involve manual observations (e.g., [18]), requesting workers to participate in surveys (e.g., [19]), or conducting interview studies (e.g., [20,21]). Observation can be accurate, but it cannot report the information in real time, and it is difficult to implement on a large scale. The problem with surveys and interviews is that they are often taken from subjective opinions, and workers may underestimate waste by considering wasteful activities as value-adding activities. From the perspective of accurate waste detection for workers in construction, it is crucial to develop a scalable and automated system that could measure value-adding activities and improve variability for site operations in construction.

The use of automated real-time tracking solutions for production control in construction aims to provide objective time and location information of site resources (e.g., materials and workers) in a scalable manner. The level of site operation can be evaluated based on value-adding activities and variability in work locations. In this regard, if we can implement an automated real-time monitoring system in construction sites, it is then possible to explore how site resources (e.g., labor and materials) move and stay. Then, it can be analyzed to reflect upon the magnitude of variability at the project and task levels, which contributes to eliminating waste and improving production control in construction. Since both material and labor waste often involve movement, obtaining position data of workers and materials could be necessary for analyzing wasted effort.

To achieve the objectives of measurement, good scalability and ease of implementation are required. Thus, the monitoring system should be uncomplicated to install with acceptable context-based setup efforts and satisfying detection coverage and accuracy. Identified technologies applied for monitoring resources in construction or under similar environments include passive radio-frequency identification (RFID) [22,23,24], magnetic field [25], ZigBee [26], Bluetooth Low Energy (BLE) [9,22,27,28], and Global Positioning System (GPS) [29]. Recent studies have indicated that the sensor network supported by BLE technology enables portable BLE-based beacons with easy deployability and favorable stability [30], which allows good opportunities for determining working patterns and quantifying productivity [31].

However, despite the potential of implementing BLE technology in construction projects, existing studies mentioned several issues when it comes to ensuring accuracy in the dynamic construction environment. For example, Park et al. [28] reasoned that the BLE system could show signs of instability when locating workers and other resources between work zones. Their results show that reliable signal connections can only be ensured when beacons are spaced not more than 5 meters away. This could complicate measuring variability and flows because the difficulty of defining if a worker is at a correct location can merge during the monitoring process. Furthermore, researchers also argued that the important roles of gateway placement strategies in BLE solutions should be emphasized [32] because an inadequate amount of gateways may fail to capture workers' movement sufficiently and the indoor positioning data would become void to assessing flows of workers and materials. Therefore, before BLE tracking technology is applied to analyze flows and variability from workers and material movement, proper investigation of system coverage, accuracy, and the need to apply additional heuristics for improvement should be carefully conducted to propose a reasonable gateway placement strategy in different types of construction projects. Once those abovementioned issues are addressed, the research can be further advanced to investigate how much time of workers and materials is spent on site operations and how much variability it reveals by the system to evaluate flows in construction.

In summary, the thesis is motivated by previous research where waste measurement in construction is still seen as difficult and complex. It is of great importance to develop a scalable and an automated system that could evaluate wasteful activities and enhance site operations in construction sites. In the next section, the research objectives and research questions for this thesis are illustrated in detail.

1.2 Research objectives

The overall objective of the research is to improve production control in construction by estimating workers' presence on-site at the project and task levels to support task progress monitoring and to assess task workflow and material management practice. In this thesis, the overall objective is divided into three sub-objectives: analysis of waste and value-adding time, automated progress detection in construction, and measurement of material management practice.

First, the research aims to measure the value-adding time of workers at the project level. Detection of value-adding time for workers could provide substantial benefits to the construction industry suffering from low productivity. Many waste types include movement; therefore, logically, workers being present on-site without movements would mean less wasted efforts. Therefore, the presence of workers staying at work locations for longer continuous periods of time is an essential condition to indicate the waste level. The first objective of the research is to explore how the real-time location of resources can be monitored to analyze the presence of workers in work locations in an automatic and scalable manner. Different types of projects are needed for tests to achieve the objective since multiple project-specific floor plans and layouts could impact tracking accuracy and coverage. Hence, a multiple-case study approach would benefit this research problem. The research endeavors to answer the following research questions:

1. *How can a real-time tracking system be implemented in real-size construction projects for estimating the presence of workers?*
2. *What is the accuracy and coverage of the tracking, and how can it be enhanced?*

Second, the thesis aims to address the challenge that getting accurate progress information or task-level productivity information is traditionally laborious. The research strives to explore further the presence of workers at a task level and to develop automated detection for task progress based on task-level analysis. In practice, considering task and location differences, workflow-specific metrics should be studied as complementary techniques to the presence of workers at the project level. Aiming to analyze task-level workers' presence to enable a better understanding of task workflows and to automate progress detection at the task level, the research further aims to answer the third research question of the thesis:

3. *Can the indoor positioning data be used for automatic task progress detection and for evaluation of task workflows in construction projects?*

Third, the research attempts to apply the real-time indoor positioning system to evaluate the interactions of the material and labor flows, with the goals of estimating the performance of logistics by looking at labor and material flows altogether. As one of the material management practices, the kitting logistics solution [33] was selected as a suitable practice because the solution requires material kits to be delivered directly near work locations where the interaction level of workers and materials would remain relevant and tracking flows of both workers and materials in work locations could become possible. Previous research has indicated notable periods of time when workers are absent from work locations [33], so an investigation of how the kitting solution influences the presence of workers was considered as an interesting line of research. Finally, the thesis also aims to gain new insights relevant to the evaluation of material management practices (e.g., the kitting solution) and enhancement potentials by tracking both labor and material kits at the same time. For this part, the research aims to answer the following research question:

4. *How can the presence of different site resources (workers and materials) be analyzed for evaluation of a material management practice?*

1.3 Structure of the thesis

This thesis is organized into two parts. The first part includes six sections. Section 1 presents an overall introduction of the thesis that includes the general outline of the research, the objectives, the proposed research questions, and the structure of the thesis. Section 2 provides necessary research background knowledge, elaborating task workflows in construction, material management practice, and the technical setting for the monitoring methods. Section 3 illustrates the methods and the materials for the current thesis, including the research design, the infrastructure of the monitoring system, and the case descriptions. Furthermore, Section 4 focuses on results presenting the artifact development and its associated results, including suggested heuristics for tracking improvement after the analyses of data accuracy and coverage, assessment of the presence of workers at both project and task levels, detection of task progress and validation, and, finally, development for metrics related to the evaluation of material management practice based on the presence of site resources (e.g., labor and materials). Section 5 discusses the generalizability of the system to enhance production control in construction, presence index (PI) comparison, overall contribution to scientific knowledge, managerial implications of the research, and the limitations for future improvement. The final section provides a summary of the research for the conclusion of the thesis.

The second part of the thesis collects the three original publications included in the thesis.

2. Research Background

2.1 Task workflows in construction

A smooth flow of tasks in construction is frequently disrupted. These disruptions are often caused by the unreliable flow of work prerequisites, requiring improvisation and work under suboptimal conditions (known as making-do) [4,34]. These disruptions can cause unplanned, wasteful activities, such as rework and non-value-adding movements between work locations [3]. To improve productivity and decrease waste, it is critical to understand the concept of flows in construction.

The concept of flows in construction evolved from the manufacturing industry, where once Shingo and Dillon described the differences between two flows: process flow and operations flow [35]. They referred to process flow as the progress of a product along a production line, whereas operations flow as individual actions performed on a product at workstations.

However, the understanding of flows in construction is not well defined because the flow of trade crews conducting tasks in construction through work locations is different than the flow of products through a production line in manufacturing [36]. The major difference is that manufacturing workers assembling a product in the production line are fixed at their workstations, while the construction product does not move. Therefore, it is of significance to define and understand flow concepts in construction.

Built upon Shingo's conceptual source regarding the difference between flows in process and operation, Koskela et al. defined the concept of flows in the context of lean construction [37]. They pointed out that operations are referred to as the "*individual tasks performed by crews and represented in activity networks*" and processes are referred to as "*the flow of work (construction products)*," which they claimed as "workflow" in construction. Based on the definitions, Sacks [36] summarized the "workflow" from the lean construction perspective as the flow of work packages, where work packages involve all elements of "crew, product, work method, design information and equipment." Accordingly, Ballard [38] argued that researchers should "*shift in focus from productivity and resource utilization to work flow as the instrumental cause for performance improvement*," because "*that impact is more important than the improvement in productivity of any single player*" (element). Therefore, workflow is one of the important factors that impact overall project-level outcomes in construction.

Product flow in construction was metaphorized for the flow of location, where Kenley and Seppänen [39] described this phenomenon as incoming materials and elements installed in the operations conducted by trade crews in work locations, similar to the products moving along a production line in manufacturing. When looking at the product flow in construction based on the view of the flow of work locations, Sacks [36] pointed out that the sequence of location and workstation congestion should be noted to impact productivity and variability. More specifically, the sequence of production in work locations in construction can be fixed (e.g., structural works), in contrast to the changeable sequence of products in manufacturing among operational tasks [36]. In addition, for construction projects, it is possible and even common to have more than one task performed in one individual work location at a time. It was referred to as "stacking of trades," which can lead to workspace congestion and reduction in productivity [40]. Therefore, despite attempts to improve product flow in a single trade, it is also important to consider multiple resources among different operations in construction.

Based on the view of the importance of product flow as a metaphor for location flow in construction, Kenley and Seppänen [39] emphasized their review of workflow in construction as location based rather than activity based. They considered the importance of location perspective in construction workflow, referring to location as "*a construction embodiment of a product that flows through a set of production operations*." However, although they made useful analyses to characterize bad workflows, such as discontinuous workflow, overlapping production in one work location, and sequence changing of tasks in workflow, they have not accurately measured the task workflow to quantify in time, for instance, what the optimal workflow is.

Improving workflow can be achieved by eliminating waste and minimizing variability in work because variability in workflows is well connected to waste in work locations. Serpell et al. [41] pointed out that waste was something in the form of deviations from a stable flow. Researchers [12] further described that waste could take two different forms: inactivity and rework, which results from mistakes in tasks or from poor flows of resources and materials. Furthermore, the concept of waste can be understood as wasted time perceived by workers as useless activities on-site, which is a way to quantify waste by clarifying the difference between the situation when the workers performed correct tasks and the situation where the workers feel "we did not get much done today" [42]. Kalsaas [42] classified wasted time from two perspectives: (1) unnecessary fragmentation of the work, which involves "moving, setting up tools, fetching and moving of materials etc." Changes of tasks from those activities result from "making-do," which leads to tasks starting without all required materials, equipment, and workers. This phenomenon generates disruption of workflows and waste on-site, which is also reflected in the workers' actual presence on-site. (2) Faulty execution, which includes reworks that register wasted time from errors and lack of coordination. To tackle waste and variability, researchers have previously attempted to improve construction planning and scheduling.

Construction planning is of significance to enhance workflows, and efforts to develop theories and methods in construction schedules are being constantly sought. Ever since the 1950s, the critical path method (CPM) has been introduced and implemented, benefiting the construction industry in the field, such as planning and controlling of projects and communicating plans [43]. However, CPM does not account for flow. There has been advocating for a transition from monthly CPM schedule updates toward more in-time task planning and control [21]. In addition, under lean principles, more flow-related planning methods have been designed and developed to address workflow variability [7] and waste elimination. For example, Takt planning and Takt control (TPTC) [44], the Last Planner® system (LPS), the location-based management system (LBMS), and their combinations [21] have demonstrated benefits in improving construction workflow and production control [21,45,46].

In TPTC, variability is reduced by decreasing the batch size, standardizing the process using small areas with consistent duration (Takt time), and making any deviations visible to all. To protect against remaining variability, capacity buffers are used in each Takt area. Case studies have reported improved productivity and resource utilization and reduced cycle times [45,47,48]. The key to the success of Takt time planning is to set a defined time when a product must be produced to match the rate that the product is needed (supply rate matches demand rate) [49], which attempts to generate reliable work production by driving out all variability using capacity buffers. However, there is a lack of research to monitor progress information using Takt to measure variability and waste in a timely and automatic manner. More specifically, there is still a black box within each Takt area and Takt time for real-time production control.

The LPS was developed to support project teams in creating a network of commitments and decreasing batch sizes by dividing them into small assignments. The characteristic of the LPS is using pull techniques, which means working backward from a scheduled finishing time that demands the tasks to be defined and sequenced to meet the set finishing time [21]. Based on pull techniques, LPS divides the work into assignments and measures whether those assignments were completed, for example, by measuring the percent plan complete (PPC) and addressing any failures by using a root cause analysis [4]. Even so, LPS still misses detecting all waste within those assignments. Furthermore, previous research shows that LPS improves production flow, but that LPS may be a fragile indicator that is correlated with performance and characteristics of production flow because it revealed that high PPC could still lead to unstable workflow in construction [50]. In addition, existing metrics such as PPC still only considered activities between the start and end times of a task or within a weekly review so that the waste detection inside of tasks may be seen as a black box in those small assignments specified by LPS.

The LBMS is used to plan continuous workflow to maximize learning effects and prevent the risk of waiting and additional mobilization. Furthermore, when data on actual production rates and labor consumption are collected, the LBMS can be used to monitor progress, estimate performance metrics, and predict future production levels in construction [47,51]. Similar to Takt time planning, LBMS also intends to generate a continuous flow of tasks within a set of production areas and rates for each phase of the work [47]. However, in LBMS, it is also the weekly cycle of control and difficulty to get actual resource data. Overall, despite the implementation differences, what is common to all these different methods is the goal of improving the reliability of construction production workflow. Progress monitoring is an essential part of these methods.

However, research has shown that the timely data collection of accurate progress information is a key challenge in production control [46] for task workflows. As one step forward, the LBMS aims to apply weekly control [51], the LPS works on weekly plans, and Takt control happens within cycles of each Takt time. Overall, production problems occurred only at a weekly frequency (e.g., in [52]) since usually a one-week timeline was selected as the resolution for the lean approaches in construction projects. In summary, it becomes a generic issue that all those common lean approaches appear to use weekly time frequency, therefore leaving a black box where waste and variability are left unnoticed based on the current time detail of monitoring. Hence, there is likely a lot of room for improvement within the box (i.e., inside of task workflows) so that waste and variability can be revealed and measured to support timely production management decision-making in construction.

In this regard, it is insufficient to determine important factors that impact waste and variability in task workflows with a one-week monitoring frequency because this should need the information of accurate time spent when site activities are undergoing. Conventionally, waste from tasks was examined by observations [23], but manual inspection and following workers on-site are heavily tedious, which make data collection progress slowly, and there is no feasibility to proceed with a continuously long-term work process on-site [53]. Furthermore, manual monitoring from construction personnel for data recording can hardly make a useful response to a quickly changing construction environment [53]. Also, inaccurate self-entries of data during progress monitoring are problematic. Therefore, real-time methods to estimate wasted effort and task progress are needed.

2.2 Monitoring materials and workers for production planning and control improvement

In the context of material flows, when we look at the process (the flow of the product), we see a flow of material in time and space [35]. This can therefore be understood as material that flows through different work locations over time as part of process flow. Efficient process flows require removing, as far as possible, wasteful steps such as moving, waiting, and inspection, and minimizing setup times and rework [36]. However, numerous wasteful activities can result from material handling and therefore hinder material flows on-site. For instance, Teizer et al. [15] monitored shell and interior construction and indicated notable wasteful activities, including (1) unnecessary handling of material, (2) searching for the right resources, and (3) waiting to use the resource, all of which caused wasted effort related to material mishandling. Misplaced materials cause waste, such as rework and delays in tasks [16], both of which hinder process flows in construction.

A smooth material flow in construction is critical, but there are many challenges with it. For instance, the challenge to match between site demand and supply in materials on construction sites can greatly influence wasteful events occurring in material flows. This is because both demand and supply can be variable in construction projects, and variability is critical to production system performance in terms of time efficiency [17]. Unreliable material supply would unavoidably increase the wasteful activities in time, such as labor looking for materials instead of working, which impacts matching the material demands and causing delays [17]. In addition, material management impacts operation flows in work locations because it is possible for more than one trade crew to work in a single location using the same material [40]. Therefore, to alleviate the effects of variability of supply and demand in material management, it is essential to obtain timely information about materials, such as knowing whether they are utilized at the right time and in the right locations.

Field material management should also be seen as an issue of unitary coordination of both workers and materials in construction. In construction, material installation can be thought of as a set of site assembly and utilization operations [17]. The coordination was mentioned in the Assembly Operations Law [6] as "*the performance of an assembly operation is degraded by increasing any of the following: (1) number of components being assembled, (2) variability of components arrivals, and (3) lack of coordination between component arrivals.*" However, the study only concerned the coordination related to material handling and management but has not covered much the process flows of both workers and material in work locations. It is important to address both workers and materials because processes cannot proceed until all necessary materials and required personnel are present for operations in work locations. The matching problem of workers and materials can be augmented due to the variability of both resources [17]. In this regard, an optimal workflow can be achieved if materials are delivered to and used in work locations matching the time for the required task operation performed by workers. In this way, it also helps logistic providers to adjust material delivery schedules on a better calibrated just-in-time basis.

Following a just-in-time basis to decrease variability of labor and material flows in work locations, a kitting logistics solution is developed to synchronize material deliveries associated with the daily tasks of workers at the location level [33]. Originated in the manufacturing industry, the concept of kitting refers to packing and delivering materials required for assembly tasks into one package to designated work locations [54]. Kitting logistics solutions benefit stabilizing production flows in construction by avoiding material inventories and requesting necessary materials tailored for individual work locations. The kitting solution enables more efficient and timely material deliveries directly to the work location on-site. Since the kits are sent and handed over near the precise work locations that need the materials, the management practice contributes to productivity by fulfilling more efficient material usage at the workplace and decreasing the wasteful time of workers searching for parts needed for the tasks [33]. Allowing workers to use the materials in the kits close to the work locations instead of walking from separated storage rooms, the kitting logistic solution (as part of material management practice) ameliorates overall work progress and production stability in construction [33].

Even still, the kitting practice faces difficulties of tracking in a timely and efficient manner, for instance, when workers utilize material kits in work locations. An increasing number of new technologies and sensing devices are considered to play a major role in improving material-handling management practices in construction up to date [55]. Site material management may significantly benefit from automated monitoring technology and automation in detection [56]. For instance, the deployment of material monitoring practices can improve worker productivity [57] and also eliminate the time that workers have to spend looking for suitable materials [58]. This would help solve the current difficulties of traditional material management, which is unstructured and hard to digitalize due to a lack of clear logic to connect massive different materials. Furthermore, the kitting practice requires smooth information flows between operations, creating potential for automation [59]. To date, there is a lack of automated methods currently existing to evaluate the effectiveness of the kitting solution by any key performance indicators (KPIs). Thus, the kitting logistic solution was selected as one of the management practices in construction, aiming to evaluate the material flows and logistics performance.

2.3 Automated monitoring systems

The aim of the thesis is to reveal the waste in the construction process, to monitor task progress, and to evaluate material management. With automated monitoring systems implemented in construction sites, it is possible to assess task workflows by addressing waste and variability and to evaluate materials and workers based on their common movements. Previous studies on automated monitoring systems are reviewed here, relating to the tracking methods that have been implemented in construction projects. The tracking methods can be typically categorized by vision-, mobile-, and radio-based technologies.

Current state-of-the-art vision-based techniques support the identification of different classifications of activities and the detection of task-accomplished levels [60]. However, to achieve the research objectives of this thesis, it requires the techniques to be able to reveal waste, monitor progress, and evaluate logistics performances. The issue with vision-based methods is that they often demand large datasets to train the system to achieve these three objectives. In addition, false negatives and false positives of tracking signals, such as problems of occlusion, can also be found in state-of-the-art solutions [61]. To date, there is still a black box in construction among task operations where workers, materials, and equipment may be engaged with notable non-value-adding events. Often, non-value-adding activities reflect waste occurring on-site that requires the sensing of movement. With vision-based technologies for detection of movement in construction sites, the system requires addressing both object detection and object tracking because applying a detection-only method could just provide positions of entities that appear in the camera views, but the method could not assign identity information to the detected entities for presence [61]. This constraint could possibly be tackled by applying tracking methods. However, though tracking methods offer trajectory data, they still need to be provided with the position of the object at its first appearance in a camera view, which may lead to tracking failure due to occlusion issues [61]. Therefore, compared with radio-based tracking methods, vision-based technologies may encounter mismatch errors that could be propagated and impact the later matching process of other pairs [62], which potentially damages task progress detection in production control. Furthermore, vision-based technologies typically require workers to dress specific clothes (e.g., hi-vis apparel) in order to fulfill suitable tracking conditions for image recognition [63], which can be seen as extra work for participants to bear. The privacy issue of tracking people on-site with cameras is also a sensitive topic in construction. In summary, video-based techniques could be used to monitor progress if given large enough training datasets, but it is challenging to use the techniques for presence detection or logistics evaluation.

In addition to vision-based methods that typically depend on site cameras and video analyses, mobile-based applications could also be possible for the detection of site occurrences and the classification of workers' activities [53]. For example, embedded accelerometers and gyroscope sensors to capture the body movement of workers have been tested in the data collection process for automated activity recognition [53]. Alternatively, QR code scanning from smartphones to collect workers' task information has also been explored. For instance, Raj et al. [64] illustrated the advantages of QR codes with small maintenance requirements and affordable infrastructure costs in a building navigation system for closed buildings. However, these tracking methods have similar limitations; that is, they require workers to carry phones in jobsites at all times and to ensure phones are at sufficient battery. Furthermore, some mobile applications rely on information entered by workers themselves (e.g., [65]; to ask workers about their own entries of start and finish times). However, the detection of movement may not be accurately observed by these systems that depend on reporting information from workers because there could be a clear difference between actual data and expected data of workers' trajectory in the field workplace [66], which leads to the expected reporting data far from objectivity.

Some of the abovementioned limitations could be tackled by using radio-based resource tracking methods in construction. Such sensor-based monitoring technologies are typically based on radio signals transmitted among tags (such as beacons) and gateways [67,68]. It was reported that radio-based tracking methods may be less accurate (e.g., more than 1 meter of accuracy for RFID and BLE technology) compared with vision-based tracking methods (submeter level), but they are particularly reliable in object detection and identification [67]. Due to the good capability of providing reliable identification information to exclude false detection, which is critical for context-aware site management [67], radio-based tracking methods may be a more suitable approach to monitor multi-resource movements and task progress, while constant accuracy of resource and task identity need to be ensured during the entire tracking process.

Several common radio-based tracking methods include RFID [23,69], magnetic field [25], ZigBee [26,66], Ultra-Wideband (UWB) [70], and BLE [9,32,71]. These methods all appear to reduce the working efforts in manual data collection in construction while providing timely data feedback via automated processes. Specifically, the RFID tracking method allows for monitoring using active or passive tags with scanners or antennas that read the tags [69]. The merit of applying passive RFID in construction is that those tags do not need a separate power supply and the infrastructure is deemed as small, inexpensive, and can be attached to almost all materials [15]. However, passive RFID tags cannot be ensured with good functionality in a large-scale environment [72]. In addition, potential signal blocking is still regarded as an issue in chaotic indoor construction environments, which hinders the signal quality of this method [15,23]. Cheng et al. [70] explored an integrated approach by applying data from real-time location sensors (RTLSs) and thoracic accelerometers to obtain a thorough understanding of the site situation picture of workers' activities based on the fusing information from two specific sensing technologies (UWB and physiological status monitors [PSMs]). However, the scope of the study was to assess task activities by classifying them into different time groups, such as time of travel, rest, and wrench. Therefore, the research did not consider either interactions with site resources other than workers or task differences in a multi-task environment, which is hard to implement to achieve the objective of this thesis. Furthermore, Lin et al. [66] proposed a ZigBee-based tracking solution, aiming to develop a real-time monitoring system to gain more comprehensive knowledge of workers' behavior. They achieved a 3–5 meters' accuracy of the system by implementing a dynamic wireless sensor network connected with mesh communication technology, but the underlying method has not been tested under an indoor construction environment.

Compared with other tracking methods, the BLE solution has some advantages in indoor construction environments. (1) BLE is reliable and reasonably accurate for indoor tracking workers and materials in construction. Previous research suggested that BLE beacons can achieve encouraging results for proximity detection because the beacons are light, resistant to various weather conditions, show acceptable battery life with minimal false-negative alerts, and have low input of infrastructure and time for calibration [25]. In addition, a recent study also found that the sensor network applying the BLE tracking method could reach a positioning accuracy of 5–10 meters in construction projects, and the portable BLE beacons show easy deployability and well-performed stability [30]. Those characteristics of BLE beacons provide promising opportunities for identifying work patterns and quantifying productivity in construction [31]. (2) BLE is cost-efficient and easy to deploy and maintain. Therefore, BLE technology can be a suitable candidate for continuous and relatively long periods of progress monitoring in construction tasks [9]. (3) BLE tracking supports multiple resource tracking with good scalability, which is crucial in detecting the interaction of workers and materials [73]. Thus, the BLE technology also shows good potential for tracking both labor and material flows with the goals of evaluating a specific material management practice using a real-time monitoring system in construction. To the best of our knowledge, no previous research to date has applied the BLE tracking solution to explore the interactions of construction labor and materials in indoor building environments.

3. Methods and Materials

3.1 Research design

The overall objective of this thesis is to automatically estimate workers' presence on-site at the project and task levels to support task progress monitoring and to evaluate task workflow and material management practice. The initial indoor tracking system was technically developed by Behnam Badihi, and the thesis author conducted the data collection field tests and analyses using the tracking system. The design science research approach [74] was followed in this thesis.

Design science research focuses on the development and performance of designed artifacts to solve problems [75]. More specifically, it includes two main perspectives: (1) to create new knowledge based on designing novel or innovative artifacts (things or processes) and (2) to analyze the use of the artifacts and/or the performance through reflection and abstraction. Algorithms, interfaces, and system design methodologies are commonly applied in design science research processes [75].

The proposed research methods, steps, and goals (indicated by each publication) are summarized in Table 1. In this research, the thesis aims to develop novel evaluation metrics in real construction projects to improve production control in construction, which are the artifacts created in the thesis. More specifically, the thesis intends to discover how the system can be used to evaluate value-adding time at the project level, analyze individual task performance, and automate progress measurement and material performance. Therefore, the creation of relevant metrics through these analysis and evaluation processes forms the artifacts to improve operations management and production control in construction. Hence, the design science research approach is a suitable research method.

The proposed system was validated and enhanced using data from several actual construction projects. This thesis covers different construction project types in the industry, such as residential buildings, office buildings, and renovation projects. The different project types selected aim to cover various construction processes. A summary of the research methods is presented in Table 1.

Table 1. Summary of research methods

Step 1: Understanding	**(i) Identify a relevant problem**	1. How can a real-time tracking system be implemented in real-size construction projects for estimating the presence of workers? 2. What is the accuracy and coverage of the tracking, and how can it be enhanced? 3. How can task progress be automatically detected for the evaluation of task flows in construction projects? 4. How can material management be automatically evaluated based on the presence of different site resources (workers and materials)?		
	(ii) Deep comprehension of the topic	Theoretical references: lean philosophy esp. waste, LPS, LBMS, BLE indoor positioning	Case 1: Plumbing renovation Case 2: Office building Case 3: Residential building Case 4: Plumbing renovation Case 5: Renovation project	
	(iii) Proposals to improve and measure	1. 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. 2. Propose how to measure the task progress information from real-time tracking so that the data can be used to automatically detect the start and finish times of the construction tasks and calculate the uninterrupted presence at the task level. 3. Propose how to measure the time-matching level of labor and material kits from real-time tracking so that the data can be used to evaluate the underlying kitting material management practices.		
Step 2: Analysis and Development	**(iv) Implement and test the solution (case studies)**	System implementation in five construction projects (cases 1–5)	Data analysis and simulation	Model refinement
	(v) Theoretical contribution of the solution	Final version of the integrated model: 1. to estimate the uninterrupted presence of workers at the project and task levels; 2. to detect task progress of start and finish times; and 3. to evaluate material management practices based on the presence of both workers and materials.		
	(vi) Examine the applicability of the solution	System implementation in various case projects (cases 1–5)		

This research followed a series of steps to ensure that the study was conducted objectively. The first three steps aim to ensure that the system was implemented according to the floor plans, and the system's accuracy and coverage were also estimated: (1) The system was implemented in jobsites following the floor plans; (2) the researcher conducted simulated movement of task processes in work locations, and system data accuracy was checked on the grounds of the known trajectory of researchers (ground-truth data); and (3) system coverage was first examined based on researchers' ground-truth data, and next project-level coverage of workers was evaluated.

Furthermore, for the first two research questions in this study in order to examine the overall detection of workers' presence at the project level and the system's improvement potential for coverage and accuracy (Publication 1), the following steps are necessary after the first three steps proposed above: (4) heuristics were applied to improve coverage of the system; (5) comparison of tracking results with and without heuristics was conducted to evaluate improvement potentials; and finally (6) uninterrupted presence at the project level was measured.

For the third research question, in order to develop an automated method for measuring task progress, such as start and finish times based on the indoor positioning data (Publication 2), the following steps are presented after the first three steps proposed above: (4) identifying the start and finish time from the presence of workers in a specific workplace and planning information; (5) validating the automatically measured task start and end time from the self-report information, and investigating any notable differences; and (6) calculating the task-level presence of workers in different work locations and discussing the use of a task-level presence.

For the last research question, in order to evaluate the proposed kitting material management practice based on the integration of monitoring labor and materials in construction (Publication 3), the following steps are presented after the first three steps: (4) calculating workers' time-matching levels and material kits; (5) evaluating the flows of material kits; and (6) evaluating time-matching level in all tracked locations and for different tracked workers.

3.2 System and software architecture

In order to track workers and materials, BLE beacons were used for the monitoring process. The BLE beacons periodically broadcast information, including the media access control (MAC) address of the device, minor and major numbers, and the universally unique identifier (UUID) of the device. Based on the proposed architecture, only the MAC address of the beacons is exploited, and these addresses are used to be connected to the profile information of workers taking beacons. The beacons broadcast at a frequency of one second, and the transmission range differed from some meters to several tens of meters depending on the transmission power of the beacons. Raspberry Pi acted as a gateway to gather the broadcasted data from neighboring beacons and send the data to the cloud. Figure 1 describes the system and software architecture that consists of data processing systems, the main data structure, and the data flow chart.

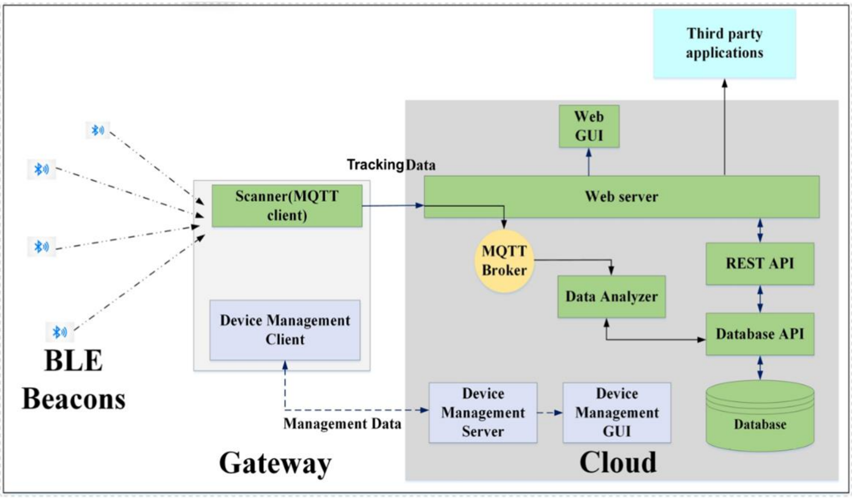

Figure 1. The architecture of indoor tracking applications for construction sites [22]

The gateways constantly scan the periodic signals from the close-by beacons and pass the signals by applying the Message Queuing Telemetry Transport (MQTT) protocol. The frequency of publishing the data is set to be 1 Hz; i.e., the gateways transmit the data in intervals of one second. The broker in the cloud pushes the data out to those clients that have previously subscribed to a specific topic. In the architecture, the Data Analyzer module subscribes to a topic published by clients in gateways. Namely, the Data Analyzer module collects data produced by gateways.

Gateways calculate the received signal strength indication (RSSI) from the beacons and transmit RSSIs together with the MAC address associated with respective beacons. RSSI is the magnitude of distance to a gateway: the further the beacon to the gateway, the smaller RSSI. It is the criteria applied in Data Analyzer to decide beacon locations.

The method for location determination in the current architecture is from the Cell of Origin method [26]:the location of a beacon is measured by the closest gateway that captures its signal. When the signal of a beacon is captured by multiple gateways in the neighborhood, the gateway that obtains the strongest signal is selected to be the location of the underlying beacon. The Data Analyzer module compares the RSSI of the beacons and assigns location information to a gateway that obtains the strongest signal. This captured signal is highly dynamic under indoor conditions and is frequently changed due to the multi-path propagation of the wireless signal resulting from refraction and reflection in the surrounding environment. Previous studies have discussed reliability as part of the flickering problem in real-time tracking [76–78]. To tackle the problem and balance RSSI values, the system applied an array of N recent RSSI values of every beacon in every gateway. Storing a new value in the array filters out the oldest value. Using the method to average the last N value of RSSI, the outlier values are deleted, and the flickering issue is handled.

The location of every gateway placed is known; thus, an approximate location of a beacon can be measured by the closest gateway that captures it. Figure 1 depicts two data flows between gateways and the cloud: (1) tracking data applied for beacon whereabouts and (2) management data applied for managing parameter settings and for configuring gateways through a graphical user interface (GUI) of the Device Management module. These two parts of the data are independent of one another.

The Data Analyzer module is also in control of storing data in the database after analyzing and filtering the tracking data. However, this is indirectly executed via a database API (application programming interface) module. Lastly, the data in the database can be used from a third-party application through a REST (representational state transfer) API.

3.3 Case description and system implementation

Table 2 presents a summary of the case descriptions, their respective main objectives, the data collection process, and the 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 (cases 3, 4, and 5). Those different construction spaces for the tests were selected because it is important to explore the gateway placement, coverage, and system accuracy in multiple different cases. Cases 1, 2, and 3 mainly aimed at analyzing the presence of workers at the project level from different project types, developing methods to improve the system's coverage and accuracy, and discussing gateway placement strategies (Publication 1). Case 4 aimed at analyzing the presence of workers at the task level for task progress detection (Publication 2), and case 5 aimed at analyzing the presence of workers and material kits as a combination of site resources to evaluate the kitting solution as part of material management practice (Publication 3). All cases were selected to cover different gateway placement strategies, such as [small locations (case 1), large open locations (case 2), tracking at the floor level (case 3), and tracking at the apartment level (cases 4 and 5)]. The goal is to explore different monitoring details of resolution (project or task level) and to investigate monitoring possibilities for different site resources (labor and material kits) to serve the overall purpose of improving production control and eliminating waste in construction. Therefore, schedules for cases 1–3 were not collected, as the aim for those cases was to develop project-level metrics.

The case studies were started by obtaining floor plans for each project and discussing with site managers where the gateways could be implemented. Because of the different sizes, types, and objectives of each project, the number of gateways placed in jobsites varied case by case. This resulted in multiple gateway installment strategies, which will be compared in subsequent discussions. During the monitoring period, gateways require electricity and to be constantly connected to the Internet. Beacons were distributed to workers who agreed to be monitored, and they would need to sign an explicit consent form to participate in the study. They were instructed to carry beacons at all times on jobsites.

Depending on the cases, the number of distributed beacons differed from 8 to 16 due to the project size and the willingness of workers to participate in the study. The beacon transmission power in cases 1, 3, 4, and 5 was kept at the default level (12 meters), while in case 2 power was slightly raised to reach a range of 15 meters because of the large open space on every floor. The study aims to achieve reasonable coverage while minimizing the potential flickering impact. The flickering impact refers to the situation where nearby gateways were close to each other and incorrect detection occurred due to reliability issues.

Table 2. Description of case studies

Case number	*Project type*	*Tracking period*	*Number of tracking devices*	*Main objective*	*Cost of the hardware **	*System setup time and maintenance*
Case 1	Residential building: plumbing renovation (3318 m^2)	From September 1 to October 13, 2017	15 beacons to workers 23 gateways on one jobsite	Worker tracking at apartment level	1325 EUR	8 hours for system setup; 1–2 hours weekly for maintenance
Case 2	Office building (22400 m^2)	From September 21 to November 30, 2017	13 beacons to workers 21 gateways on one jobsite	Worker tracking in open spaces	1207 EUR	6 hours for system setup; 1–2 hours weekly for maintenance
Case 3	Residential building (3869 m^2)	From October 18, 2017, to January 31, 2018	11 beacons to workers 10 gateways on one jobsite	Worker tracking at the stairwell and floor levels	594 EUR	5 hours for system setup; 1–2 hours weekly for maintenance
Case 4	Residential building: plumbing renovation (1600 m^2)	From March 8 to June 1, 2018	8 beacons to workers 9 gateways on one jobsite	Worker tracking at apartment level	527 EUR	The initial system setup for half a day; weekly (1–2 hour each time) site visit to maintain the system
Case 5	Residential building: renovation project (1200 m^2)	From May 26 to June 29, 2018	8 beacons to workers and 8 beacons to material kits 9 gateways on one jobsite	Worker and material kit tracking at apartment level	559 EUR	4 hours for the initial system setup; 1-hour weekly site visit for system maintenance

*(4 EUR / beacon + 55 EUR / gateway)

In the five 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; and (7) type of tracking resource (workers or material kits). The time intervals in the tracking raw dataset convey information about a worker, trade, location, and the corresponding time durations in that detected location. A new time interval is created in the system while a worker moves to a new location and is detected by the next gateway. During the tracking time, additional beacons were registered with the system when new workers started in the project. Ongoing maintenance work was needed in the case of possible sudden changes in the site environment, which sometimes required re-positioning gateways because of the availability of power supply over time. However, the projects did not make significant changes in the layout of locations during data collection.

Because a suitable placement of gateways is vital for validity of the tracking results, a systematic process for installing gateways was conducted: (1) collect floor plans for each project and mark the preliminary gateway location according to entries, exits, and natural locations boundaries by walls; (2) decide the number of gateways required and configure the gateways associated with serial numbers in the system; (3) meaningful gateway setup in jobsites according to the installation plan and testing for power availability and connectivity; (4) inspect whether gateways are successfully registered and connected to power and the Internet; (5) associate the gateway serial numbers with the floor plan where every gateway would represent a meaningful location in jobsites.

3.3.1 Case 1. Plumbing renovation

The plumbing renovation case study was implemented in Helsinki, Finland. The participant company was a general contractor for the selected plumbing renovation project. The simplified section of the jobsite is illustrated in Figure 2. Work locations were one- and two-bedroom apartments, which were divided with concrete walls and slabs. The total area was approximately 1106 m² per floor.

Figure 2. Case 1 schematic plan with gateway placement marked

In this case, the study was conducted to install as many gateways as possible, depending on power availability, to ensure that most of the apartments would be covered individually by gateways. Gateways were installed along the entrance areas (4 gateways), storage room areas (6 gateways), stairwells/corridors between apartments (6 gateways), and inside of apartments (7 gateways). Because of the availability of temporary power, some of the apartments had a dedicated gateway, while on some floors, one gateway in the corridor served two apartments. Entrances and storage areas were considered places where no value-adding work was conducted, while corridors and apartments were considered places where value could be added except for apartment A2, which served as the site office during the tracking time.

3.3.2 Case 2. Office building renovation

The second case was an office building renovation project located in central Helsinki, Finland. The participant company was a general contractor for this project. The building consists of seven floors (approximately 2800 m^2 per floor) above ground and one floor underground. At the time of the study, the interior walls had not yet been erected; therefore, each floor was an open space. Due to limited access to temporary power on the site, only a few gateways were installed on each floor, so there were areas where the signals of beacons could not be captured by any gateway. In this project, the site office did not have a gateway because the social facilities for workers were in the same location. Therefore, visits to the site office in this case study are considered as off-site time, while in some other cases the visits to the site office could be on-site but not in the work location. Tracking was undertaken after demolition, so the conditions were similar to those of new construction projects. The simplified floor plan is presented in Figure 3. The entry gateways at the front gate and back gate were recorded as non-work related because they were close to a storage area, and the other gateways were considered gateways in work-related areas.

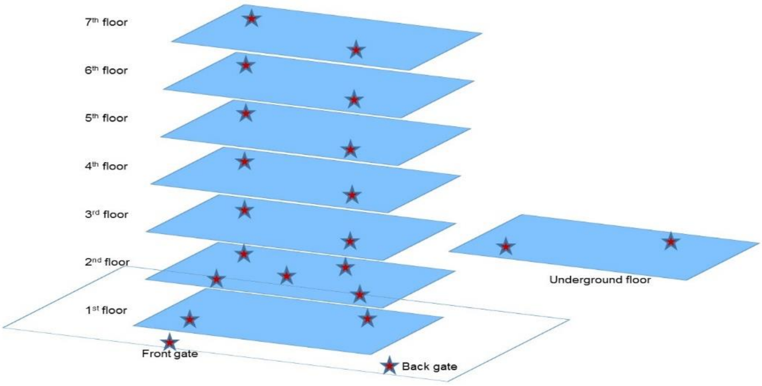

Figure 3. Case 2 schematic plan with gateway placement marked

Because there were open spaces without signal coverage, this case provided an opposite case compared with the plumbing renovation case (such as case 1), where the gateway placements were compact, and the signal coverage was comprehensive. By learning the difference, it was possible to discuss the impact of gateway placement strategies and the feasibility of the system in different types of construction projects.

3.3.3 Case 3. Residential building

The third case study was a new residential building project in Helsinki, Finland. The partner company was a general contractor for this project. The simplified floor plan is presented in Figure 4. The building consists of three stairwells and a site office. Each stairwell connected five floors. Gateways were installed on each floor of stairwells A and B, as well as in the office area. There were two gateways placed 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 inside the building. At the time of monitoring, the entry of A & B stairwells was not ready; thus, there was no gateway at A & B stairwells' entry. Construction work had not started on stairwell C; therefore, no gateways were placed there. Cases 1 (plumbing renovation) and 3 are conceptually similar, but the gateway placement in case 3 is at the entry area to each floor, whereas gateways were inside apartments in case 1. In both cases, the apartments were separated by concrete walls. The differences between these two cases can provide a better understanding of gateway placement strategies with concrete separating walls.

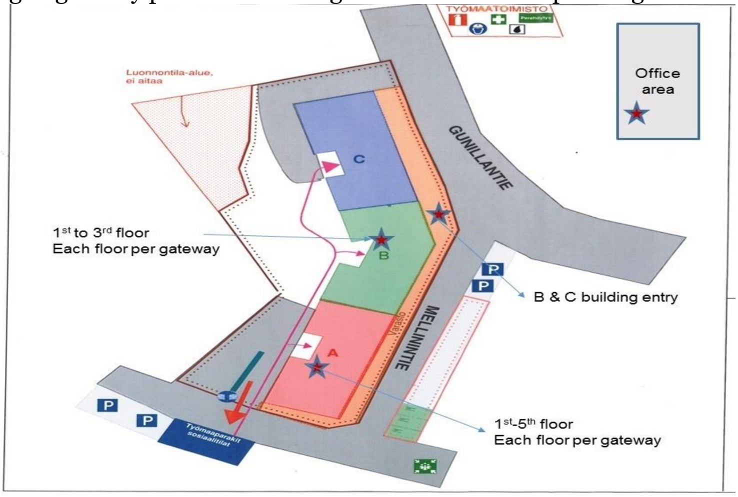

Figure 4. Case 3 schematic plan with gateway placement marked

3.3.4 Case 4. Plumbing renovation

Since case 4 aims at evaluating the presence of workers at the task level for task progress detection, a residential apartment renovation project located in Helsinki, Finland, was selected as the case for two reasons: first, this type of project (plumbing renovation) had been measured with indoor positioning technology in case 1 before this case; and second, the researchers had access to the resource-loaded task-level schedule. Therefore, other information was also collected, such as task start and end dates, and some tasks were selected for testing the schedules. The monitoring process took place from March 8 to June 1, 2018. The residential building included seven floors, with four apartments on each floor (see Figure 5).

The BLE beacons were distributed to eight workers. The placement of nine gateways is illustrated in Figure 5. To place the gateways, the guidelines were followed and developed from the previous results of cases 1–3 (reported in Publication 1). Three gateways were placed at the exit locations (two on the ground floor and one in the construction site office) and one in a selected apartment on each floor (the red stars in Figure 5). Based on the logic of the workflow, which was from the top to the bottom floor, it was reasonable to monitor one apartment on each floor. The chosen apartments on each floor were one-bedroom apartments with an area of approximately 50 m^2. All selected apartments had the same layout; thus, each apartment's wall structure and location were identical, which made it possible to compare the tracking data among the chosen apartments. Due to the lack of required power supply for the gateways, it was not possible to install any gateway on the second floor.

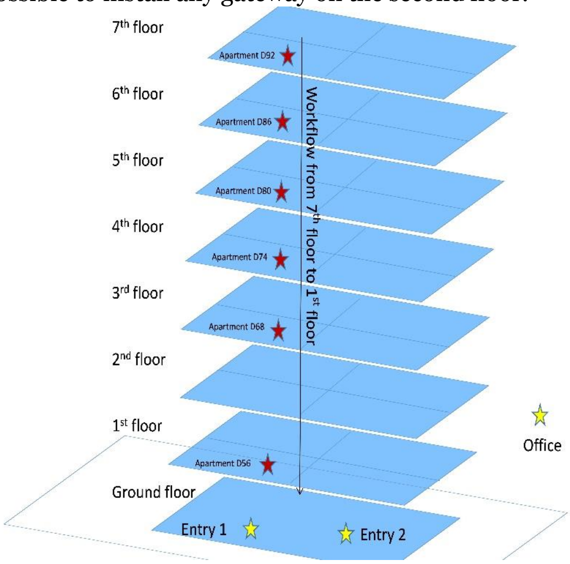

Figure 5. Case 4 schematic plan with gateway placement marked

Table 3 summarizes the selected tasks, which can be broadly classified into two groups. First, workflow 1 (bathroom workflow) is a set of tasks with a logical sequence based on technical dependencies in a constrained space. In the bathroom, the selected tasks had to be completed in the following sequence: masonry of shafts → preparation of concrete floor pours and pouring → waterproofing → tiling → joints → suspended ceiling → caulking of the suspended ceiling → painting of the suspended ceiling → furnishing → finishing. Second, workflow 2 (kitchen workflow) is a set of tasks that are not technically dependent on bathroom workflow tasks but have resource dependencies, such as shaft drywall and kitchen furnishing.

Generally, 12 tasks, including three trades (carpentry, tiling, and painting) in six work locations [floors 7 through the ground floor (see Figure 5)], were monitored.

Table 3. Summary of tracked workers in case 4

Tasks **(Abbreviations)**	**Work trade**	**Workers assigned to the task**
Masonry of shafts (MS)	Carpentry	Carpenter 1 Carpenter 2
Preparation of concrete floor pours and pouring	Carpentry	Carpenter 1

(PP)		
Waterproofing (WP)	Tiling	Tiler 1
Tiling	Tiling	Tiler 1
Joints	Tiling	Tiler 2
Suspended ceiling (SC)	Carpentry	Carpenter 1 Carpenter 3
Caulking of suspended ceiling (CSC)	Painting	Painter 1 Painter 2
Painting of suspended ceiling (PSC)	Painting	Painter 1 Painter 2
Furnishing (Fu)	Carpentry	Carpenter 1
Finishing (Fi)	Carpentry	Carpenter 1
Shaft drywall (SD)	Carpentry	Carpenter 2
Kitchen furnishing (KF)	Carpentry	Carpenter 1 Carpenter 4

3.3.5 Case 5. Residential building: renovation project

Case 5 aimed at analyzing the presence of workers and material kits as a combination of site resources to evaluate the kitting solution as part of material management practice. The case selected was a renovation project in Helsinki, Finland. The construction work was conducted in a three-floor building in June 2018. The project implemented a kitting logistics solution due to the potential to enhance workplace utilization by minimizing the wasted efforts of material transportation from storage areas to the site [33]. One gateway was placed in every apartment; therefore, a total of nine gateways were placed (eight gateways in eight apartments and one at the entry on the ground floor). Eight workers (including carpenters, plumbers, plasterers, and bricklayers) assented to be monitored and carried the beacons; each of the eight material kits was also attached with a beacon for tracking. Because of the different sizes of the apartments, the quantities of materials in the kits could be different, but the materials were the same for the selected tasks in each apartment. Each material kit was assigned to each apartment for the tasks illustrated in Table 4. Each kit contained the necessary material parts for the renovation project in the respective apartment. The possibility of attaching both material and labor allowed one to analyze the interactions of workers when they performed on-site material-related works.

Figure 6 presents a simplified floor plan, with gateways marked in the figure. Table 4 presents the task schedule for monitored workers and tasks. Each tracked task follows the same sequence from apartments A3 to A4, A8, A7, A1, A2, A6, and A5. Each successor apartment in the sequence for the same task is always scheduled half a day later than the former apartment, excluding weekends. The scheduled work hour is from 7:00 to 11:00 in the morning for the first half day and from 11:30 to 15:30 in the afternoon for the second half day. The tasks shown in the table included only work that was done in bathrooms. Workers from other trades (such as electricians and painters) could also be on-site during the tracking period in the workflow, but their tasks were not tracked.

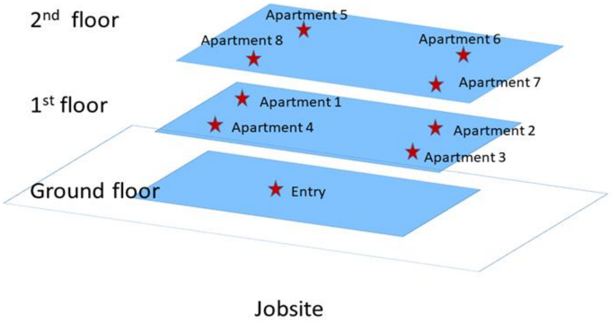

Figure 6. Case 5 schematic plan with gateway placement marked

Table 4. Task schedule summary for tracked workers and tasks

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

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

4. Artifact Development and Results

This section describes in detail system validation and improvement (including data accuracy, coverage, and improvement heuristics), artifact development (including methods and processes to detect workers' presence at the project and task levels, to evaluate task progress, and to evaluate a material management practice by monitoring the overlapping presence of workers and material kits), and finally the results.

4.1 Data accuracy of the monitoring system

To develop the first artifact regarding improving the quality of raw data from real-time tracking, necessary analyses must be conducted to evaluate the system's accuracy and coverage for monitoring in construction.

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 detected by a gateway, and (4) end time detected by a gateway. Each time interval in the raw dataset has these four attributes. The first three cases (Publication 1) were used to illustrate the data accuracy level of three different project types (plumbing renovation, office open-space building, and residential building). A total of 29,877 recordings of time intervals were made from case 1, 18,620 from case 2, and 3,664 from case 3.

Before developing metrics important for production control, it is necessary to ensure that the system detects accurate data as a starting point for further analyses. Data accuracy was defined as the capability of the system to detect tracked objects in the correct location at the correct time. There are many reasons why the system could record beacons in the wrong locations. For example, if the same beacon was detected by multiple gateways, the signal strength determined where the beacon was. Signal strength can also fluctuate randomly because of interference or obstruction. In this study, data accuracy was evaluated by collecting ground-zero data from two researchers who went to construction sites, moved from one place to another, 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-recorded by the researchers. Because the gateway placement strategies in these projects were different, the process was able to provide valuable information on how monitoring device placement plans impact accuracy (research question 2).

In practice, data accuracy was evaluated based on how many correct and incorrect minutes were recorded in the system when they were compared with the actual position of the researcher during that minute. Table 5 shows in detail how actual movements were matched with the system recordings of one researcher in case 1. Due to the complex environment of jobsites, some gateways need to cover multiple apartments; for instance, in the "recorded location" column, the gateway "A1A2" covers both apartments A1 and A2. As long as the recorded location matches any of the actual locations during the same time interval, the time can be assumed to be recorded correctly. For example, if the raw data location in the system was labeled "A1A2" and the actual location of the researcher was "A1," the time interval was considered detected in the table. Researchers also moved around during the accuracy test, in which case the "actual location" column of the table shows two locations (e.g., A1–C11). In that case, the 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 nonmatches were reviewed in detail and categorized. In the first category, an incorrect gateway detected the beacon for a period of over a minute (nonmatch category 1). For the second category (nonmatch 2), the gateways were close to each other, but the incorrect detection was less than a minute. This category can be named flickering, which has often been mentioned as a reliability issue in previous studies on real-time tracking (i.e., [76–78]). The third category (nonmatch 3) was a coverage issue in which the beacon was not detected at all.

Table 5. A researcher's actual and recorded locations: an example of 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	**Nonmatch 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	**Nonmatch 2**
8:30–8:31	0.8	A2	A2	**Match**
8:31–8:31	0.7	A2	A1	**Nonmatch 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	**Nonmatch 3**
8:36–8:38	1.4	A1	A1A2	**Match**
8:38–8:39	1.6	A1	Not detected	**Nonmatch 3**
8:39–8:40	1.0	A1	A2	**Nonmatch 2**
8:40–8:41	0.8	A1	Not detected	**Nonmatch 3**
8:41–8:44	3.1	A1–C11	A2	**Nonmatch 1**
8:44–8:47	2.8	C11	C11C12	**Match**
8:47–8:50	3.1	C11	Not detected	**Nonmatch 3**
8:50–8:52	2.2	C11	C11C12	**Match**
8:52–8:56	3.7	C11	Not detected	**Nonmatch 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	**Nonmatch 3**

9:05–9:23	18.0	B5	B5B6	**Match**
9:23–9:24	1.2	B5	B entrance	**Nonmatch 1**
9:24–9:25	0.4	C12	C entrance	**Nonmatch 2**
9:25–9:25	0.3	C12	C9C10	**Nonmatch 2**
9:25–9:27	2.0	C12	C11C12	**Match**
9:27–9:28	0.5	C12	C entrance	**Nonmatch 2**
9:28–9:29	1.1	D14	D entrance	**Nonmatch 1**
9:29–9:35	6.1	D14	Not detected	**Nonmatch 3**
9:35–9:40	4.7	Ground floor	D entrance	**Match**
9:40–9:43	3.2	Ground floor	Not detected	**Nonmatch 3**
9:43–9:44	0.9	Ground floor	B entrance	**Match**
9:44–9:44	0.5	Ground floor	A1	**Nonmatch 2**
9:44–9:46	2.2	A2	A2	**Match**
9:46–9:55	8.7	A2	Not detected	**Nonmatch 3**
9:55–9:56	0.5	A2	A2	**Match**

The results of the data accuracy and coverage analysis of the three cases are presented in Table 6. The total matched time varied substantially between the cases, and it was the highest in case 3, with stairwell and floor level gateway placement in the 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 enhancing the coverage were needed for the investigation.

Table 6. The data accuracy analysis: summary of the researchers' locations in the three cases (all times in minutes)

Project	**Total matched time**	**Total time of "nonmatch" category 1 (accuracy)**	**Total time of "nonmatch" category 2 (flickering)**	**Total time of "nonmatch" 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%)

4.2 Data coverage at the worker level

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

To evaluate data coverage, the researchers' and workers' location data were analyzed in the first three cases. The "coverage ratio" was defined as the share of time the beacon was actually detected inside 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 covers the jobsite 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 a site office that 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 7 presents the detected time, total operational time, and coverage ratios in cases 1, 2, and 3 compared with the overall researcher coverage ratio.

Table 7. Workers' overall coverage ratios in the three case projects compared with those 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	66072	98191	67.3%	72.1%
Case 2. Office open-space renovation	47242	154482	30.6%	45.1%
Case 3. Apartment building	60818	121976	49.9%	88.8%

Compared with researcher movement analysis, the project workers' overall coverage ratios are lower on average. This is expected because workers can be genuinely off-site, for instance, conducting errands in inventory areas. In addition, social facilities did not have gateways, except for case 1, where the site office was in one of the apartments and also served as a break room for workers. Hence, the expected maximum coverage ratio was approximately 88% (510 minutes minus 60 minutes of breaks) in cases 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 a gateway, which could be one of the reasons that case 2 reached a very low coverage level. To summarize, the actual coverage ratios were relatively low, thereby indicating either considerable off-site time or incorrect detection. This results in problems when calculating the project-level uninterrupted work location presence (research question 3). The conclusion of the coverage analysis can be drawn that (1) there is a need to develop some heuristics to enhance the coverage ratio and (2) gateway placement can significantly affect the coverage ratios; thus, finding a good placement strategy for each project is critical to ensure data quality. Next, focus is placed on ascertaining how the coverage could be improved by implementing heuristics in the system.

4.3 Improving coverage through heuristics

As shown in Table 1, to address the first artifact, the system's coverage needs to be enhanced so that the quality of raw data from the monitoring can be strengthened. A heuristic technique was adopted 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 workers during those time intervals in which their beacon was not detected by the system. To develop systematic patterns, the researcher's 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 in the context of the construction project.

It can be reasoned that nondetected time could result from two reasons: (1) true off-site time when workers are away from the 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 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 8 presents possible scenarios of this heuristic rule.

Table 8. Scenarios to identify the status of undetected workers

Time interval	Gateway (location)	Scenarios
Time 1 Time 2 Time 3	Exit gateway Undetected Exit gateway	(1) Off-site time
Time 1 Time 2 Time 3	Exit gateway Undetected Non-exit gateway	(2) On-site time
Time 1 Time 2 Time 3	Non-exit gateway Undetected Exit gateway	(3) On-site time
Time 1 Time 2 Time 3	Non-exit gateway Undetected Non-exit gateway	(4) On-site time

The following are the four possible scenarios:

1. If a worker disappears at an exit location and later reappears at an exit location, the off-site 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 the actual movement of the researcher on-site was known to test the accuracy of the system, it was possible to use that data to see how heuristics affect the data quality. Table 9 shows the improvement in coverage ratios in each case 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 also lower after heuristics than in cases with more compact gateway placement (case 2 compared with cases 1 and 3).

Table 9. Researchers' coverage ratios before and after heuristics (all numbers in minutes except for coverage ratios)

Project	**Before/after heuristics**	**Total matched time**	**Total time of "nonmatch" category 1 (accuracy)**	**Total time of "nonmatch" category 2 (flickering)**	**Total time of "nonmatch" category 3 (coverage)**	**Coverage ratio**
Case 1. Plumbing renovation	Before heuristics	52	11	4	27	71.2%
	After heuristics	69	11	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 10 presents the workers' coverage ratios before and after heuristics at the 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). 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 rest area 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 a gateway, which could be one of the reasons that case 2 reached a very low coverage degree. 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.

Table 10. Workers' coverage ratios before and after heuristics in cases 1, 2, and 3

Project	*Before or after heuristics*	*Coverage ratio*	*Daily detected time (minutes)*	*Total time of the day (minutes)*
Case 1	Before	67.3%	66072	98191
	After	89.5%	87886	
Case 2	Before	30.6%	47242	154482
	After	77.5%	119658	
Case 3	Before	49.9%	60818	121976
	After	80.1%	98666	

4.4 Detecting workers' uninterrupted presence in work locations (Publication 1 [22])

With improved coverage after the heuristics, it is possible to evaluate the share of uninterrupted presence (research question 1). As introduced in the case study description (Section 3.3), uninterrupted presence analysis was conducted for cases 1, 2, and 3 (Publication 1). Presence in a work location is a necessary but not sufficient precondition for value-added work, so when the share of time in work locations goes up, the share of value-adding time typically 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 visiting a location). Therefore, although the proposed system cannot see if the value was added in a location, it is possible to estimate a useful metric that is correlated with true value-adding time by looking at uninterrupted presence in locations. Different tasks have different setup times [79]; thus, the length of time workers need to be present in the same work location before they could possibly add value can differ between tasks. In those cases (1, 2, and 3) where uninterrupted presence analysis was conducted, task differences were not considered, but different overall threshold times were used to see how they would impact the share of uninterrupted presence.

Table 11 shows the share of uninterrupted presence (the PI) at threshold values of 0, 1, 5, and 10 minutes 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 without interruptions before the time interval is included in the calculation. The PI 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 the PI from 1 to 5 minutes and less of a drop from 5 to 10 minutes. This indicates that many of the tracking time intervals are between 1 and 5 minutes. 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 5 minutes other than minor punch list work or site supervision. Site supervisors and forepersons were excluded from this analysis because we assumed that, in contrast to tradespeople, they can create value by merely visiting a location briefly. As expected, the heuristics increased the PI most in projects with a sparser gateway placement (cases 2 and 3). PIs at the 10-minute threshold value were the highest in the apartment building project (case 3) and lowest in the office renovation project (case 2).

Table 11. Presence indices at work with different threshold values for each case (time in minutes; excluding the 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	59009	87793	67.2%	53.0%
			1	55502		63.2%	50.1%
			5	36694		41.8%	33.2%
			10	26566		30.3%	25.1%

Case 2. Office open-space renovation	From September 21 to November 30, 2017	8	0	33947	93045	36.5%	18.2%
			1	33511		36.0%	18.2%
			5	27322		29.4%	13.7%
			10	22786		24.5%	10.8%
Case 3. Apartment building	From October 18, 2017, to January 31, 2018	11	0	65696	121976	53.9%	30.5%
			1	64773		53.1%	30.3%
			5	50411		41.3%	22.2%
			10	43284		35.5%	19.8%

The impact of heuristics was highest at lower threshold values because most of the time heuristics fill in the blanks of very short time periods. The investigation was made further to evaluate the impact of heuristics on the validity of the PI. 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 minute time intervals when the worker was not detected (Table 12). It can be argued that this is a valid increase of the PI 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 the densest gateway placement strategy. However, cases 2 and 3 had a higher amount of time intervals that were over 20 minutes and thus were considered present, even though the system did not detect the workers.

Table 12. Distribution of counts and percentage of time intervals the heuristics applied in all cases

Case study project	Time intervals 0–5 minutes (counts/percent)	Time intervals 5–10 minutes (counts/percent)	Time intervals 10–15 minutes (counts/percent)	Time intervals 15–20 minutes (counts/percent)	Time intervals 20+ minutes (counts/percent)
Case 1. Plumbing renovation	15891	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%

4.5 Detection and validation of task start and finish times (Publication 2 [9])

4.5.1 Detection of task start and finish times

After demonstrating the system implementation and addressing the coverage and accuracy issues, it is then possible to explore the method deeper into the task-level detail. In practice, this means applying the indoor positioning system to detect task progress, including the start and finish times of tasks (artifact 2 in Table 1). Case 4 (Publication 2) was used to investigate how the task start and finish times could be analyzed based on the monitoring records of workers. This was done by implementing the following steps:

1. Because the first task in the bathroom workflow (MS) was always scheduled one full day ahead of the first task in the kitchen workflow (SD) for each location, analyzing the bathroom workflow was started first. According to the schedule, there was a time when the task “preparation of concrete floor pours and pouring (PP)” in the bathroom was conducted at the same time as task SD in the kitchen workflow, but those two tasks were scheduled for two different workers, so their presence could be differentiated.
2. In both workflows, the first detected uninterrupted presence on each floor was compared with the schedule of a task that was the closest to that presence so that we could determine from which task in the workflow the worker had started the job.
3. Task switching took place between two tasks within the same workflow. If the given task’s successor was scheduled for the same worker, it could be assumed that the task switch happened when there was an absence of at least 4 hours at that location after the last presence of the task had been detected; 4 hours was used because all tracked tasks at a single location were scheduled for 4 hours, except for kitchen furnishing. If no absence period longer than 4 hours could be found, the method took the scheduled start time of its successor and used it to search for the closest detected uninterrupted presence to determine the time of the task switch. When determining absence, the absence time outside the construction hours was not counted: (1) the workday started at 7:00 a.m., (2) the workday ended at 3:30 p.m., and (3) a lunch break was between 11:00 a.m. and 11:30 a.m. In this case, the task switch rule was applied to the following task sequences where the same workers were doing multiple tasks in the same location: MS-PP, WP-Tiling, CSC-PSC, and Fu-Fi.
4. If the given task’s successor was scheduled for different workers other than the one for the given task, it could be assumed that the task switch occurred when the first uninterrupted presence of the successor task was detected, regardless of the length of the absence time between the two tasks. This task switch scenario was applied to the following task sequences: PP-WP, Tiling-Joints, Joints-SC, SC-CSC, PSC-Fu, and SD-KF.
5. In summary, the start time of a given task was the start of the first detected period of uninterrupted presence, and the finish time was the end of the last uninterrupted presence of that task until the task switch.

The scheduled and tracked start and finish times for the selected tasks were derived based on these task-detection rules. Information related to the bathroom on floor 5 is presented as an example. Figure 7 illustrates how the raw data on floor 5 for consecutive tasks (waterproofing, tiling, and joints in the tiling trade) were used to determine the tasks’ switching. Task switch 1 took place when there were 272 minutes of absence after the waterproof task’s detected presence, which was longer than 4 hours. Task switch 2 took place when the other tiler’s presence was detected, regardless of the absence of time length. March 24 and 25 landed on the weekend, so no presence of workers was detected.

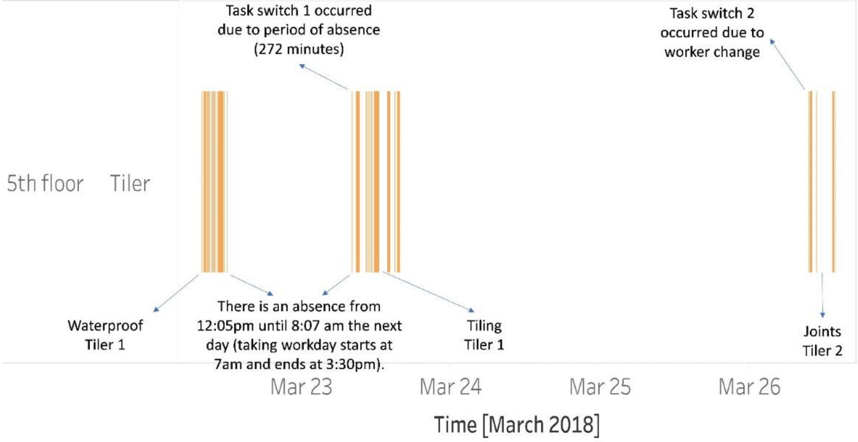

Figure 7. Task switch example for three consecutive tasks on floor 5

Based on the steps, the calculated task start and end times with schedule were compared as part of the development process of the artifacts in methods. Table 13 presents the plans and tracking results of the tasks in the sequence of how work was actually performed, from the tasks “masonry of shafts” (top) to “painting of suspended ceilings” (bottom). There is a discrepancy between the tracked and planned start and finish times. This is expected because workers do not or cannot follow their plans in practice all the time.

Table 13. The scheduled start and finish times of tasks on floor 5 compared with the results based on the real-time tracking system

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

	13:30	8:00	9:50	13:06

In summary, the presented method can tentatively answer the third research question on how to automatically identify the task start and finish times based on the information of worker presence in specific locations. The automatically detected information on the task start and finish times in different locations will be validated against the construction workers' self-report information in the next section.

4.5.2 Validation of detection of task start and finish times

After analyzing the uninterrupted presence of workers at the project level and describing the methods to measure the task progress information from the real-time tracking system (the development of artifact 2), it is then possible to explore the uninterrupted presence of workers at the task level (Publication 2). In Section 4.3, the heuristics of using the monitoring system to detect task start and finish times have been described, but it is needed to validate the results so that the evaluation for uninterrupted presence at the task level can be objectively conducted. Case 4 (Publication 2) was used to investigate the validation for detecting task start and finish times.

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

Table 14 summarizes the differences between the system-detected results and the workers' self-report results, giving a total of 11 tasks (excluding the task "shaft drywall"). A 4-hour time difference was used to divide the observations into "accepted" and "not validated" categories because all the tracked tasks at a single location were scheduled for 4 hours, except for the task of kitchen furnishing (3 hours). Workers were supposed to enter start and finish events into the system "in real time," but some entered information later. In those cases, some inaccuracy was expected in the data. The natural way workers segment their time is based on breaks, which occur roughly every 2 hours (i.e., morning before coffee break, afternoon after coffee break, before lunch). For this reason, 2 hours (= 1 break) is categorized as "close" and 4 hours (= 2 breaks) as "accepted"; 4 hours is considered a limit for acceptance (= 2 breaks) and the "accepted" category was further divided into "close" (2–4 hours, 1–2 breaks) and "validated" (<2 hours, <1 break).

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

1. If the time difference between self-reported data and tracking results is longer than 4 hours, the results are considered “not validated.”
2. If between 2 and 4 hours, the results are “close.”
3. If less than 2 hours, the results are “validated.”

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

In summary, for the task start time, it was found that 35 out of 45 observations (78%) were “validated” or “close,” and for the task end time, 27 out of 45 locations (60%) were “validated” or “close” (Table 14), resulting in a total of 31% of observations that were categorized as “not validated.”

Table 14. Differences between self-report data and tracking results of workers (number of observations)

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

For each of the 11 tasks, all detected time intervals over the whole dataset were evaluated to see how many of those were between the self-report start and finish times (Table 15). In total, 92% of the detected time intervals occurred between the task self-report start and finish times.

Table 15. Count percentage of the recorded time intervals within the self-report data of each task (the whole dataset)

Tasks	*Number of time intervals between the self-reported start and finish time*	*Total number of time intervals*	*Percentage*
Masonry of shafts	129	129	100%
Preparation of concrete floor pours and pouring	171	171	100%
Waterproofing	94	101	93%
Tiling	108	120	90%
Joints	33	43	77%
Suspended ceiling	67	72	93%
Caulking of suspended ceiling	217	281	77%
Painting of suspended ceiling	69	72	96%
Furnishing	25	30	83%
Finishing	94	110	85%
Kitchen furnishing	381	381	100%
Total	1388	1510	92%

Several observations were made based on the validation results. (1) The task start and finish times, as reported by the workers or site managers, were generally close to the automatically derived task start and finish times (see Tables 14 and 15). However, there were issues with the self-report data. For example, there were cases in which the start and finish times of a task at one work location were reported with the same timestamps in the SiteDrive system. This confirms that manual data collection and entry are subject to human error. (2) The self-report data represent the time range of the task execution but do not show how much time the workers were present at the work location. For example, although a worker reported the whole day for their tiling task on March 23 on floor 5, the tracking system identified several periods when no one was present. Time gaps are visible both in the handovers between tasks and within the task execution periods. Based on the tracking data, the tasks were regularly suspended, but in the self-report data, these suspensions were not captured. Therefore, the self-report data do not give an overview of how the workers' time was actually used on-site.

Next, workers' uninterrupted presence was visualized in all tasks and work locations to obtain a broader picture of work progress (Figure 8). The figure demonstrates two workflows of tracked tasks in one timeline. The dashed lines separate the kitchen workflow and bathroom workflow on floors 3, 5, 6, and 7 in the figure, where tracking data for both workflows are available.

Due to several inaccuracies, floor 4 was excluded from further analysis. Five out of seven tasks on floor 4 were not validated due to more than 4 hours' difference between the estimated and self-recorded start times. In addition, on floor 4, uninterrupted presence was captured as related to only 7 tasks out of 12, which was the fewest when compared to other floors. For tiling on floor 4, only 59 minutes of presence was detected for tiler 1 from 12:30 to 13:52 on March 23. According to the proposed task detection rules, the presence was classified as "waterproofing," but tiler 1 reported doing this task on March 22 and "tiling" from 8:29 to 15:10 on March 23. Therefore, it appears that the period of uninterrupted presence was adequately related to the task "tiling'," but the duration was too short when compared to the self-report task duration.

The lack of uninterrupted presence captured could result from the fact that the workers may need to remove gateway power plugs at times for their own task uses but forget to plug them back in straight away. This was discovered during the system accuracy test observed by the researchers, but it was not possible to estimate how long the gateways were unplugged because the system could not determine whether the undetected time was from the absence of workers or gateway offline periods. On floor 4, the uninterrupted presence in six tasks (out of seven tasks detected in total) did not appear to be during the same time as the workers' self-report records. This suggests that the unplugged gateways did not capture the uninterrupted presence of workers during their self-report time range of the work, thus shortening the total captured uninterrupted presence on floor 4.

Furthermore, there were also problems with workers' self-report data on floor 4 to make the real picture even more complex. For example, the tiler reported working on the task "waterproofing" on floor 4 from March 22 at 7:38 to 14:31, but there were no detected uninterrupted presences during that time on floor 4. Instead, they were detected on floor 5 from 7:31 to 11:03. However, the worker also reported the exact same period for the task "waterproofing" on floor 5; therefore, the uninterrupted presence was allocated on floor 5 and not 4. It can be confirmed that workers on floor 4 were not incorrectly detected by floor 3 or 5 gateways by checking that uninterrupted presence on floors 3 and 5 matched (validated) worker self-report data on those floors, except in a few special cases.

However, even though in those special cases the uninterrupted presences on floors 3 and 5 did not match worker self-report data on respective floors, they either did not match worker self-report data on floor 4 or workers reported being on floor 4 at the same time as floor 3 or 5. Because this was the case, it was concluded that missing data was caused by unplugged gateways and workers on floor 4 were not incorrectly detected by floor 3 and 5 gateways, and other data remain valid.

For future studies, the system should be developed so that it reports unplugged gateways, and the status should be monitored more frequently and corrected (e.g., 2–3 times a week instead of weekly in this case) to avoid the potential poor quality of tracking data during the test stage caused by power supply issues.

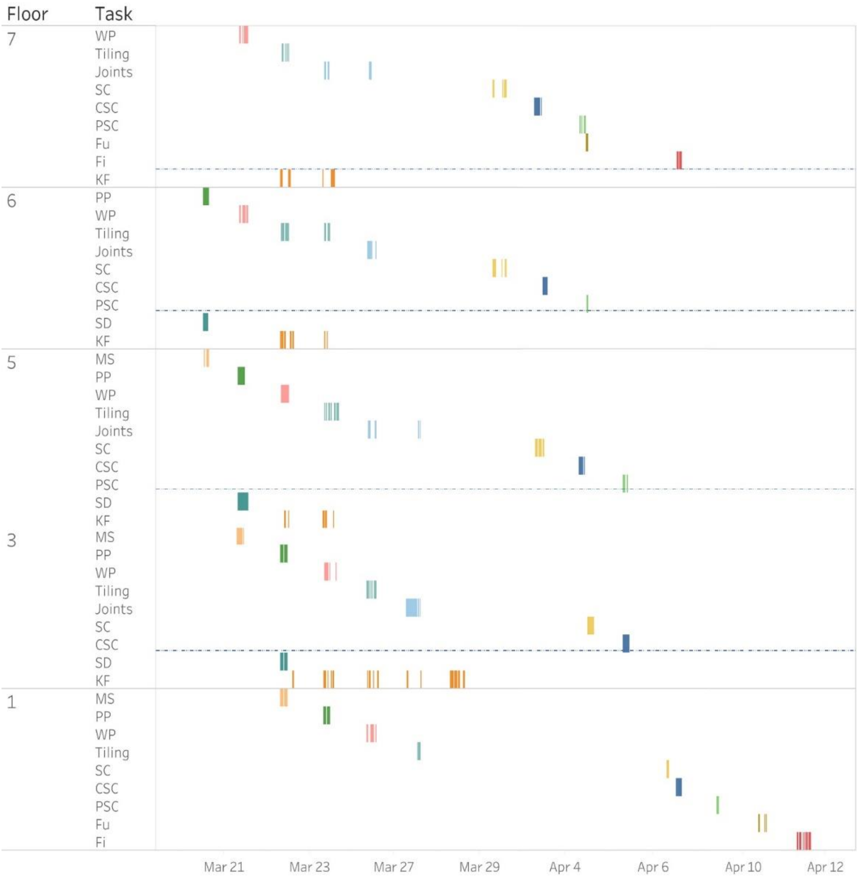

Figure 8. Tracked tasks in all locations, excluding floor 4. Abbreviations: MS, masonry of shafts; PP, preparation of concrete floor pours and pouring; WP, waterproofing; SC, suspended ceiling; CSC, caulking of suspended ceiling; PSC, painting of suspended ceiling; Fu, furnishing; Fi, finishing; SD, shaft drywall; KF, kitchen furnishing

4.6 Evaluation of task-level presence with schedules for better production control (Publication 2 [9])

After the validation, the evaluation of task-level presences was conducted to open up possibilities of using task detection data for better production control. The method used in cases 1–3 was first followed for calculating the indices for workers' uninterrupted presence for each task. The task-level PIs of the workers were calculated by dividing the total uninterrupted presence in a location between the start and finish times of the task by the actual duration of the task. The task's actual duration was defined as the duration between the first and last detected task times, excluding breaks and hours outside of standard working hours (evenings, weekends, and holidays).

$$\text{Equation 1: PIs} = \frac{\text{Uninterrupted presence time during task}}{\text{Actual duration of the task}}$$

Table 16 summarizes the results of the task-level PIs for workers in each location and the mean and standard deviation across all work locations. During the observation period, tasks were not detected or self-reported in all locations. Locations with missing data have been marked N/A (not available) in the table.

Table 16. Task-level presence indices of the workers on each floor and on average (uninterrupted presence time during task/actual duration of the task)

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

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

As a result, the phenomenon of work splitting between multiple locations was also found in the tiling task. Although the tiler was scheduled to work on floor 7, the actual presence of a tiler in that location was very low, and they spent much of this time on floor 6 (Table 16). For the waterproofing task, the crew were working on floors 6 and 7 in parallel on March 21 (Figure 9). During the crew's operational time that day (240 minutes), it was found that 71 minutes were spent on floor 7 and 107 minutes on floor 6, resulting in 74% of uninterrupted presence for the worker, but only 29% and 45% of uninterrupted work presence in the respective work locations. Here, the look-ahead plan assumed completely finishing one location before moving to the next location.

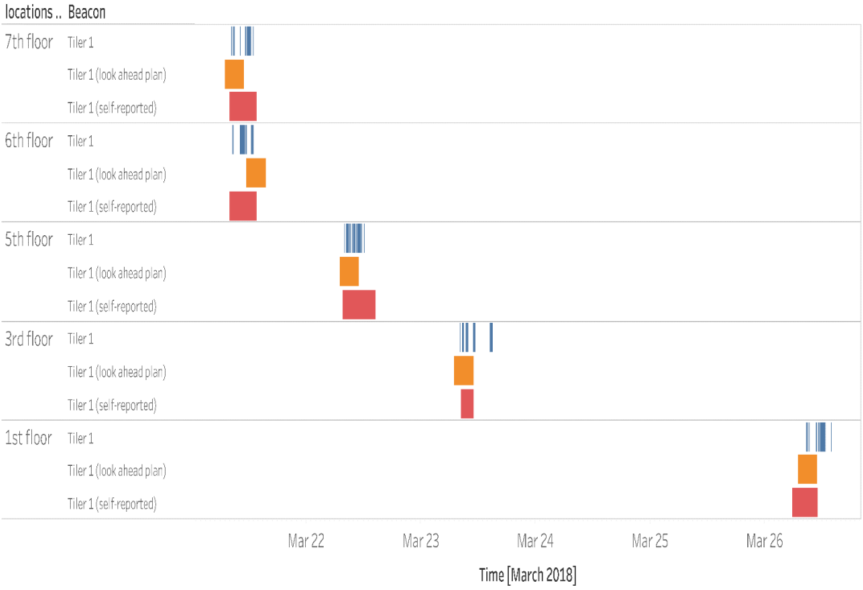

Figure 9. The task of waterproofing and workers' presence visualization against the schedule and self-report records

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

$$\text{Equation 2: PPs} = \frac{\text{Uninterrupted presence time during the task}}{\text{Planned duration of the task}}$$

where PP means presence-to-plan ratios. The PPs show how much presence is required compared with the planned duration to complete the task; therefore, the buffer included in the task's duration is measured to account for waste and variability. If interruptions could be completely eliminated by diminishing waste and improving the process, this indicates how much the schedule could be compressed. For instance, with a perfect flow in the task of "caulking of suspended ceiling," durations could be compressed to an average of 33% of existing planned durations, indicating opportunities for significant improvement (Table 17). This metric could be used to assess the potential task-level impact of lean interventions that target improving workflow, that is, by removing interruptions. Furthermore, based on equations 1 and 2, the ratio of PPs and PIs is equal to the actual duration divided by the planned duration, which has been used in other studies as a metric of schedule conformance (e.g., [80]).

Table 17. Results of PIs and PPs in all tracked tasks and their ratios

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

4.7 Monitoring the time-matching level of workers and material kits (Publication 3 [73])

Next, the thesis illustrates the development of artifact 3 in Table 1 regarding how to measure the time-matching level of labor and material kits from real-time tracking so that the data can be used to evaluate the underlying kitting material management practice. Case 5 was used to analyze the presence of workers and material kits as a combination of site resources to evaluate the kitting solution as part of material management practice. The case focused on exploring the possibilities of integrating the monitoring of labor and material resources on-site.

Since kitting material logistic solutions require each material kit to be delivered directly to each work location (in case 5, each apartment bathroom), workers' time-matching levels and material kits can be used to indicate how well the underlying kitting solution has worked and whether the workers were able to use materials from the kits to conduct their tasks in various work locations. The workers' time-matching levels and kits refer to the time period when the workers' detected presences overlap with the kits' detected presences.

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

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

1. The threshold for 10 minutes is set as the highest-tested value in case 5 because the case focuses on longer continuous working periods rather than brief visits to a location. Because one gateway was installed in each apartment in the building, it was possible to classify all detected uninterrupted worker presences by each work location (in this case, each apartment). The threshold to material kits was not applied because, due to their weight and immobility, their location is more fixed, and filtering out short visits is not required.
2. For a single apartment, all detected presences of the material kit assigned to that apartment were aggregated. For example, in apartment 1, all detected presences of the material kit assigned to apartment 1 were searched.
3. T1 = the uninterrupted presence of a worker during the same time that the material kit for that assigned apartment was present.
4. T2 = the uninterrupted presence of a worker matched the time period of a material kit that was assigned to other apartments but was present in the current apartment.
5. T3 = the uninterrupted presence of a worker that did not fall into time periods of any material in that apartment (the uninterrupted presence of the worker thus = T1 + T2 + T3).
6. T4 = the operational time of each worker, which was defined as the time from a worker's first detected time of the day to the last detected time of the day [22].
7. PI [22] = $\frac{\mathrm{T1 + T2 + T3}}{\mathrm{T4}}$.
8. The time-matching levels of workers and materials in one apartment were then estimated by comparing T1, T2, T3, and T4 with their ratios:
    (1) TMD (time matching for designated) = $\frac{\mathrm{T1}}{\mathrm{T1 + T2 + T3}}$, indicating the optimum scenario of a worker and the correct material kit in the apartment.
    (2) TMA (time matching for any) = $\frac{\mathrm{T1 + T2}}{\mathrm{T1 + T2 + T3}}$, indicating the presence of a worker together with any material kit in that apartment.
    (3) NM (no material) = $\frac{\mathrm{T3}}{\mathrm{T1 + T2 + T3}}$, indicating the share of time when the worker was present in the location without any material kits.

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

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

4.8 Monitoring material flows in relation to corresponding tasks (Publication 3 [73])

Next, the material management practice was evaluated based on the detected presence of labor and materials as a combination of site resources (Publication 3), and the methods were presented in the previous section. Case 5 was used to monitor the material flows and evaluate an applied kitting logistics solution as one of the material management practices.

In case 5, Figure 10 shows an example of one material kit (assigned for apartment A7) that was moved inside the building during the tracking period. The material kit was first detected at apartment A7 at 07:03 on June 1. The material kit was then moved to apartment A2 at 17:04 on June 17 and subsequently moved to apartment A1 at 11:04 on June 22. Finally, the kit was moved to the entry area of the building at 08:20 on June 26. Table 18 provides a summary of the moving times of each material kit, with its delivery and removal times on-site, in addition to the schedules of the task start and end times in the respective apartments. Because the presence of the material kit for apartment A3 was not found in the system due to the loss of the beacon attached to the kit, apartment A3 was excluded from the analysis.

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

Table 18. Moved times between apartments for each material kit

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

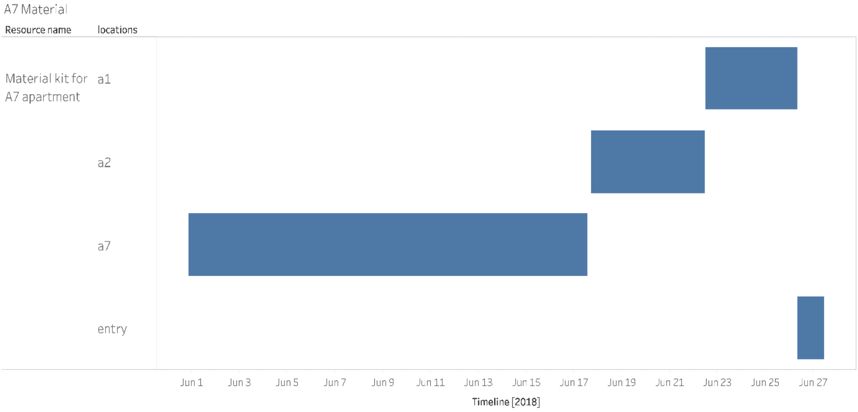

Figure 10. Material flow of the material kit for apartment A7 inside the building

For the task schedule in apartment A7, the material kit for apartment A7 was moved away from apartment A7 at 12:43 on June 17, but the scheduled end time of the last task in that apartment was at 11:30 on June 22. However, after the material kit for A7 was moved away, the material kit for A4 was moved to apartment A7 from June 18 to June 21, which covered the remaining time for the tasks required in the apartment.

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

4.9 Alignment of material and labor flow in the apartment (Publication 3 [73])

As demonstrated in Section 4.7, the workers' time-matching levels and kits refer to the time period when workers' detected presences overlap with the kits' detected presences. The interaction of material flow with the location information of workers in the apartment (Publication 3) was measured. As an example, the results of one apartment (apartment A7) were visualized, and the results of the whole dataset are presented in a later section. Figure 11 shows a visualization of the carpenter in apartment A7, while the material kits for A4 and A7 were detected as being present during the same tracking period from June 1 to 21. Figure 11 also shows that the worker was mostly present throughout the same time range as the material kit for A7 in that apartment, except for his or her presence from June 18 to 21, when the material kit for A7 was undetected while the material kit for A4 was present. Because the task of suspended ceiling plating was scheduled in apartment A7 starting on the afternoon of June 18, the worker could have taken the suspended ceiling plates from the material kit assigned for apartment A4 instead.

Table 19 summarizes the TMD, TMA, and NM results for carpenter 1 and how these values were calculated in apartment A7. Because the threshold of an uninterrupted presence for workers was set at 10 minutes, all time intervals from workers that were shorter than 10 minutes were omitted from the analysis. The 11.1% NM time of the assigned worker (carpenter 1) with material presence represents the time in which the worker was detected in the apartment without any material kits being around. A few possible reasons for this situation are as follows:

1. The worker was waiting for the material.
2. The worker had to retrieve the material from other places (or parts of other kits) and then returned to do the work.
3. Materials were delivered as supplemental orders and were not included in the original kits.
4. The worker could have been with the material kit for apartment A3 since the movement of that kit remained unknown due to the loss of the beacon for that kit.
5. The material kit was incorrectly detected (e.g., because of flickering between apartments). This impact was minimal, however, because

during the manual investigation of the time period between June 1 and 27, from the kit being delivered to the site until its removal, it was noted that only 4.33 minutes of flickering (detection in different apartments) occurred. Although the exact activities of the worker during this time were unknown, the first three points could be regarded as an indication of problems in the kitting process. In addition, two time gaps were noted in the material kit for apartment A7, between June 3 and 4 and between June 13 and 14. During these times, the material kit for apartment A7 was found in A3: from 11:06 on June 3 to 6:54 on June 4, and from 15:34 on June 13 to 7:10 on June 14.

Table 19. TMD, TMA, and NM results for carpenter 1 in apartment 7

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

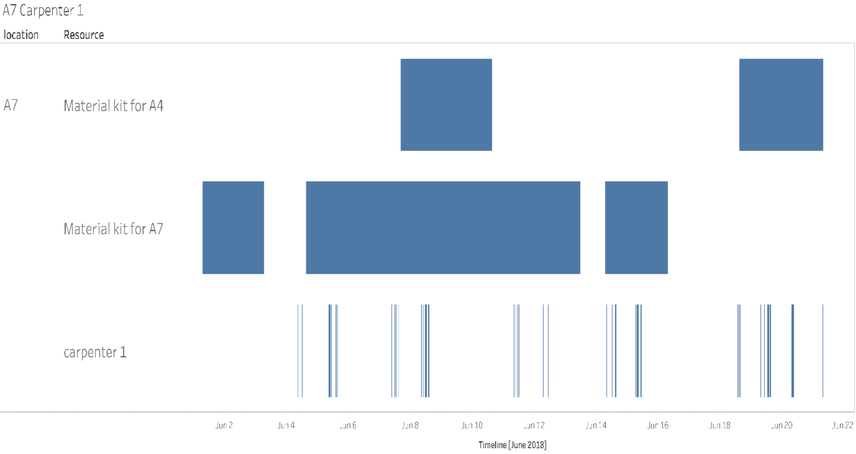

Figure 11. Movement visualization of carpenter 1 with material kits in apartment A7

4.10 Evaluation of the time-matching level in all tracked locations and for different tracked workers (Publication 3 [73])

To determine whether the tracking of material kits and labor together would add more insightful information to the evaluation of the kitting solution on-site (research question 4), the relevant metrics were calculated, summarized, and grouped by location and workers (see Tables 20 and 21).

Table 20. Summary of the time-matching levels in all apartments (all numbers in minutes, except percentages; definitions of T1, T2, T3, TMD, TMA, and NM in Section 4.7)

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

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

Next, the time-matching level was evaluated based on individual workers throughout their operations in all work locations (Table 21).

Table 21. Summary of the time-matching levels for each individual worker (all numbers in minutes, except percentages; definitions of T1, T2, T3, TMD, TMA, and NM in Section 4.7)

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

SD	1,928	285	101	56	2.3%	7.1%	4.0%	4.0%

For the individual workers, the SD values for NM were much smaller than for the locations. The problems with kitting seemed to occur mostly with carpenters, while other trades showed smaller NM values. The carpenters were scheduled to do the non-material-related task (layout) first and then to start using the materials in the kit; therefore, they might have been in work locations before the kits had arrived, thus leaving larger NM values compared to other crews. In addition, all workers were detected to have periods in the presence of material kits other than those that were designated, on average, 9.4% of the time [T2/(T1 + T2 + T3)]. The results in Table 21 show an estimate of how well the kitting solution worked for each tracked worker.

5. Discussion

In this section, the thesis first discusses the feasibility of the monitoring system implemented in construction projects and the generalizability of the proposed methods to measure workers' presences, task progress, and tracking material kits. Then, the results of different PIs are compared so that a clear contribution of this thesis to scientific knowledge can be presented. Finally, the managerial implications of the study are demonstrated, and the limitations of the system and methods are reviewed.

5.1 **System feasibility** [22]

From an implementation and data point of view, the use of the system is feasible in real construction projects. To accurately answer research questions 1 and 2, it is necessary to discuss system feasibility matters since it is the foundation for examining the system's functionality and implementation in construction. The same proposed system was implemented in five construction sites during the indoor construction phase. The 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, the tests were completed and the data useful for the analysis were also obtained. In addition, the collected data could be used for real-time production control purposes, such as locating people, materials, or equipment.

Overall, the hardware costs for the case studies were 1325 EUR for case 1, 1207 EUR for case 2, 594 EUR for case 3, 527 EUR for case 4, and 559 EUR for case 5. The gateway hardware required for each location was Raspberry Pi, with an approximate cost of 55 EUR / gateway. Therefore, the hardware, installation, and maintenance costs are quite low to achieve the functionality proposed in the thesis.

More important than the hardware costs are the costs associated with the installation and maintenance of the system. These were found to be quite modest in the selected cases. Typically, each case required half a day to investigate the site conditions and install 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 weekly or 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 hours 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. In addition, the number of gateways installed in cases was quite similar (9–23), 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 that showed the MAC address.

In addition, gateway placement appears to significantly influence the feasibility of the system implementation. The gateway placement strategy may create overlapping or blank coverage areas that influence the accuracy of data and thus uninterrupted presence analysis. The current findings indicate that gateways should optimally be placed in every work location. In apartment buildings, flickering between locations was not a major problem in this study, although the gateway spheres of influence overlapped. The concrete floors and walls were enough to dampen the signal between apartments. Therefore, in apartment buildings, 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 the flickering problem. A proposal is made that the gateways in open areas should be installed roughly at 30-meter intervals based on a beacon range of roughly 15 meters and a small overlap required to eliminate areas of no coverage.

In summary, the following four guidelines for gateway placement are proposed: (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); and (4) in open spaces at least every 30 meters. Using these guidelines, in case 1, it would have needed 11 more gateways (one for each apartment and stairwell location without a gateway). In case 2, the guidelines would lead to 2 additional gateways for all floors except the second floor (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). In cases 4 and 5, the guidelines were followed well, except for case 4 on floor 2, because it was not possible to place any gateway there. The proposed system would generalize to construction projects in the indoor construction phase, where power and connectivity can be arranged.

5.2 Relation of the uninterrupted presence to value-adding time and waste at the project level [22]

The system allows the detection of the presence of workers in work locations. Though the system cannot know whether the workers were engaged in value-adding work when they were present in the work location, it was still possible to know that if the workers briefly visited a work location or if the workers were in non-work locations, they were not doing installation work. In other words, presence is a necessary but not a sufficient condition for value-added time. Therefore, although the study cannot claim that it could accurately calculate the share of value-added time, it can still provide a metric that is easy to calculate, and it can be assumed that it is correlated with real value-added time and thus productivity. If the workers spend longer time periods in work locations and if it is assumed that the share of value-added time in work locations stays constant, an increased share of longer duration presence means higher value-added time.

The new metric using real-time BLE tracking technology combined with heuristics and threshold analysis can provide a real-time estimate of how much waste there is in the construction process. To estimate the metric PI of project resources, the percentage of time that workers spent on workplaces using different thresholds of setup time was calculated. Neve et al. [81] found that direct work constituted 26% to 36% of three examined cases, averaging 29.5% as the baseline of direct work for value-adding periods out of the total work time. The findings of 16.5%% (case 5) to 35.5% (case 3) workplace presence time with a 10-minute value-adding time threshold is in line with these results.

5.3 Generalizability of the method for tracking task progress [9]

To obtain accurate results of task progress, it is necessary to discuss the generalizability of the proposed method and future use cases for implementation. Case 4 was used for applying the indoor positioning system to track the task progress, and the generalizability of the method is discussed here. The proposed method relies on workflow dependencies. Several issues should be considered when evaluating the generalizability of the developed method. Case 4 is an example of strict and confined locations where there is a process of re-entrant flow [82] and where the same workers return multiple times to the same location to perform different tasks. On the one hand, this case project is simpler than other contexts because the small locations and strict technical dependencies enable the detection of a sequence of work activities. On the other hand, the workers were undertaking several small tasks, so the method included the added difficulty of determining the task switch in the same person's tasks. In larger and more complex projects, the tasks are generally longer. For example, Ballesteros-Perez et al. [83] reported that in building projects, the actual average duration for task activities was 11.35 days, while in case 4, the duration of most of the tasks was 4 hours. It could be argued that the smaller time resolution made tracking in case 4 more difficult because the uninterrupted presence patterns were very short to detect.

Another feature of the current project was the small locations enclosed within walls, which made the tracking system accurate. In projects with large open spaces, accuracy may not be as high as in the described case. Open spaces are also complicated in many other areas of construction management. For example, in Takt planning, there is an ongoing debate on how to define boundaries for locations, and methods such as work density planning have been proposed [84]. Open spaces are challenging because location boundaries are more or less arbitrary, and there are no natural obstacles guiding the workers to follow the plan (e.g., [39]). Accuracy problems occur, especially at the edges of work areas. In future research, the system could be generalized to open spaces by differentiating between hard technical dependencies and “soft” planning and resource dependencies [39]. Task switch in technical dependency can be determined by assuming a start-to-start relationship and classifying periods of uninterrupted presence based on their sequence. However, it can be argued that open spaces present a challenge to any kind of automatic progress evaluation system (and, indeed, even for manual observation).

Precedence relationships [85] and planning the sequence of activities are not unique to the case of this research. Olivieri et al. [86] reported that 71% of survey respondents used CPM to plan activities and that CPM includes defining logical dependencies. Some dependencies are strict and technical (e.g., walls must be built before they can be painted), while others are “soft” [39]. Several tasks can technically happen in any sequence, but not at the same time because of space requirements. The expansion of our system to these more complex contexts would require the identification of hard and soft logic. Because of generally longer durations of activities and less re-entrant work in larger projects, this should not pose a difficult obstacle, and the same approach should be usable with slight modifications. Brodetskaia et al. [82] analyzed a residential construction case of interior and finishing works for 120 apartments in 480 days. The seven activities monitored (trade activity durations varied from 1.3 days to 6.9 days per apartment) were performed by five trades (drywaller, plumber, electrician, HVAC, and tiler) with just one re-entrant flow loop (the drywaller). With these longer durations and less re-entrant flow, the task switch would be easier to evaluate. Thus, mapping periods of uninterrupted presence while knowing the approximate sequence of activities in each location should be sufficient to make reasonable progress estimates. This will be validated in future research.

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

5.4 Generalizability of the method to monitor material and labor flows for improving logistic solutions [73]

To obtain a good understanding of the results for research question 4, it is essential to investigate the generalizability of the proposed method of tracking both material and labor flows. Case 5 was used to apply the indoor positioning system to track the combination of the material kit and workers, and the generalizability of the method is discussed here.

To date, little research has focused on the combination of real-time tracking for labor and material in construction sites to address material mishandling and evaluate kitting solutions. In a few previous empirical studies, researchers have analyzed material tracking data to support better material handling and site-work performance, but the generalizability of their methods has varied. For instance, Grau et al. [56] developed localization algorithms based on a combination of RFID and GPS technologies to capture the time spent on activities directly related to tracked steel material components and to analyze the impact of the tracking application on steel erection productivity. Because GPS is unsuitable for indoor environments, however, the generalizability of this method is limited to outdoors.

Tetik et al. [33] evaluated the applicability of kitting by comparing four projects with and without kitting solutions, focusing on the impact of work performance and management requirements. While they showed that kitting solutions could improve product flow and work performance, the focus of the current study was on the effectiveness of an applied kitting solution by showing the variability of kit presences associated with workers in multiple work locations. Their method can be used to capture logistics performance on a more detailed level but is not scalable due to the manual analysis required. The current approach presents a scalable solution based on the uninterrupted presence of workers and kits in work locations that still enables the calculation of KPIs, which can be used to evaluate logistics performance.

Case 5 was an apartment renovation project where small locations (in this case, apartment bathrooms) enclosed with walls were used for analysis. Due to the project type, the accuracy and coverage values were high. In earlier research, Bluetooth-based systems showed lower accuracy and coverage values in projects with large, open areas. Kitting as a logistics solution has often been implemented first on project types with small work areas because kitting is mainly used to solve issues related to a lack of space [87]. Large open areas typically have better possibilities of storing materials, and thus the benefits of kitting may not be so large.

Generalizability to other project types should be explored in future research. The current method depends on apartment-specific material kits delivered to each work location. This type of logistics enables easy tracking because tracking beacons are required only for each kit. Although the system could, in theory, be applied to other types of materials as well, each tracked material has associated costs in time. A typical construction site contains an enormous amount of materials, and tagging all materials is not always practical. We analyzed this kitting solution in particular because of its ability to easily map materials to locations and tasks and the low number of tracked elements required. Previous researchers who have investigated materials on worksites, such as [56], have taken a similar approach by focusing on individual types of materials, although the individual materials in the kits are also of interest. In future studies, the current method could be applied to selected individual materials to determine if their movements differ from the movements of kits.

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

5.5 Comparison of different presence indices and their implications of uses

In the current thesis, multiple different PIs were proposed from five case studies. Overall, the concept of project-level PIs was derived from cases 1, 2, and 3 [22]. The task-level PIs were developed from case 4 [9], and the material-related PIs were proposed from case 5 [73]. To clarify the interrelation of all proposed indices and their use with previous studies, the discussion about a comparative study is presented in the following sections.

5.5.1 Comparison of task-level presence indices to project-level presence indices [9]

Project-level PIs are used to indicate the amount of uninterrupted presence of workers on-site in proportion to their daily operational work time for an overall project [22]. Project-level presence is a measure of efficiency at the project level. However, the task-level PI was found to vary significantly between the different tasks.

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

5.5.2 Comparison of material-related presence indices to project-level presence indices [73]

In case 5, where both labor and material kits were monitored using the indoor positioning system on-site, several indices relating to materials were developed. Compared with project-level PIs, the concept was expanded further by dividing indices into categories based on the time matching of material kits. These material-related uninterrupted presence metrics include TMD, TMA, and NM, which also require tracking data from the material kits for each work location. A project-level PI is a metric of operations flow at the project level. Instead, the material-related uninterrupted presence uses the resource flows from both material and labor perspectives, creating opportunities to evaluate the current material management practice (in case 5, the kitting solution). For instance, in case 5, the overall project-level PI was 16.5% (threshold of 10 minutes), which indicates that 83.5% of the time, the worker was either undetected inside the building or was detected at one location for less than 10 minutes. In addition, in this case, it further indicates, based on the proposed material-related PIs, that the tracked material kits were not always at the designated location, and the workers were not always present with the correct kit in the apartment.

The measurement of labor and material kit integrated uninterrupted presence creates some new and deeper analysis opportunities. The efficiency of the logistic system can be analyzed by looking at materials and labor together in connection with the schedule. For that purpose, new material-related metrics can be used to provide supplemental information on top of the project-level uninterrupted PIs. Therefore, the key motivation for conducting material and labor tracking using the indoor positioning system was to broaden the knowledge of previous case studies on material management practices.

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

1. **Waiting or other non-value-adding time spent in work locations** can be analyzed from time-matching levels between workers and material kits (TMA and NM). The smaller the NM (or larger the TMA) value, the lower the time disparity of workers who lack any kits.
2. **Success of having a correct kit in a work location** can be analyzed from time-matching levels between workers and the material kits assigned to the specific apartment (TMD). A larger TMD value implies that the assigned material kit with planned material content was more successfully adopted in practice. The difference between TMA and TMD (TMA – TMD) also suggests a time level where the kits assigned to other apartments were occupied in the apartment when the assigned kit was absent, thus indicating potential work that workers needed to use from other apartments' materials for the underlying apartment. The TMA value may indicate problems with the bill of materials used

to assemble the kit and will likely rise as a result of incorrect quantities or kinds of materials in the kits.

3. **Unnecessary inventory** can be calculated from the detected delivery time of material kits compared with the time when the first task requires the material in that kit. The lower the time gap between these two times, the less waiting or delays of the material to be used will occur. Unnecessary inventory is one type of waste related to materials, and kitting practice is typically planned to be just-in-time (JIT) [33,88].
4. **Wasted time for moving materials** can be analyzed from the moving times of material kits between work locations. With more detected moving times of material kits, workers unavoidably waste more time transporting kits to the required apartments. In an optimally working kitting process, only one movement of the kit to its location, and then one movement out, should occur once all materials have been consumed.

In summary, it can be argued that a well-performing kitting solution should have (1) high TMA and TMD values, (2) ideally little difference between TMA and TMD values, and (3) no kit movements between work locations.

5.6 Contribution to knowledge

The contribution of the thesis to existing knowledge and previous studies is summarized in the following themes: (1) PI as a proposed production control metric, (2) contribution to the detection of task progress in construction, and (3) contribution to material management practices.

5.6.1 Presence index as a proposed production control metric [22]

The research contributes to knowledge of production control metrics by proposing a metric based on workers' overall presence in work locations using a gateway and BLE beacon solution. Other approaches related to the current method to calculate the presence time include work sampling, which classifies workers' activities as one of three types: productive, semi-productive, and nonproductive [89]. Normally, work sampling has been done based on direct observation of construction workers [60,90], which is costly and not scalable. Related technology-based approaches can be divided into image-based and sensor-based approaches. For example, Luo et al. [60]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 an accelerometer (e.g., [90]). These types of approaches require extensive training datasets for each class of activity and thus cannot be easily implemented as an overall approach in all projects. The proposed rough but easy-to-deploy metric (PI), together with more detailed approaches tailored for each work type, could be a powerful and complementary approach to improve production control in construction. The metrics, such as the project-level PI, give an estimate of the overall efficiency of the work site. They can be used for evaluating the functioning of site supervision, equipment handling, material logistics, and support processes and identifying potential problems in real time. More detailed approaches aim at accurate productivity calculations for individual tasks. Both approaches play an important role in automated production control.

In summary, the developed method contributes to knowledge on lighterweight, holistic, and passive automated systems that can measure resource flow at the project level. The data from the selected cases show that this share is generally 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 unable to spend more time in the work locations? Are the workers present in the correct locations? Answering these questions requires more contextual data and combinations of different data collection technologies.

5.6.2 Contribution to the detection of task progress in construction [9]

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

Previous studies have not focused on investigating the possibility of automating the detection of start and finish times at the task level by using the BLE tracking method. The results indicate that automatic detection is feasible in the case of workflow dependencies in confined spaces, such as the bathrooms of residential apartment buildings (case 4). The results showed that it was possible to get good results in the selected case using a real-time tracking system in an indoor environment. Here, 69% of the selected locations were validated by workers' self-report data, and 92% of the tracked time intervals fell between the self-report task start and finish dates. This indicated the robustness of the proposed approach and the system for the automated detection of task start and finish times.

The possibility of integration with vision-based approaches would improve the method of tracking task progress, enabling extended contributions in future studies. For example, Zhang et al. [62] proposed a method from camera views that can be used to match construction site resources, such as workers and equipment. This method is useful for identifying workers' site activities from different camera views and automatically matching them, thereby providing possibilities for dynamically tracking the workers' continuous workflow. However, despite good research results, the study still left room for further exploration of using matched visual appearances under different camera views on-site to evaluate workflow qualities, such as proposed task-related KPIs. In addition, Yang et al. [91] studied vision-based worker action recognition based on a proposed bag-of-feature framework using a cutting-edge video representation method. Their research has the potential to contribute to the study objective since the capabilities of workers' action classification based on this vision-based approach advanced the accuracy of task progress identification and validation, thereby improving the soundness of the proposed new KPIs as PIs and PPs. The results from case 4 indicate that only an average of 34% of workers' task time was spent in scheduled work locations. It urges vision-based approaches in construction to shift focus to the time workers were actually on designated work locations, rather than scanning through a full scale of video monitoring for action recognition. This provides possibilities for integrating the BLE system with a vision-based action recognition approach to improve the identification of task progress and interruptions.

Because the proposed BLE indoor positioning system relies on location information but not on action classification to determine task status, video clips only need to be analyzed when workers are detected in designed work locations. In turn, vision-based technology for action recognition (e.g., [91]) pinpoints workers' behaviors so that task interruptions are more accurately identified for calculating PPs and PIs, which is the main contribution of the current study. Previous attempts to empirically research production at the task level have been reported as related to mainstream CPM scheduling (e.g., [43,92]), LBMS (e.g., [46,93,94]), and LPS (e.g., [4]). Although LBMS studies have tried to manually account for the suspension of tasks to obtain more accurate production rate data at a daily level, studies based on CPM and LBMS have mostly focused on comparing the planned and actual durations and dates. However, these studies have all been conducted by looking at a week's timeframe. Instead, the interruptions detected by the automated system in this paper happened continuously during implementation and were not considered by workers or superintendents in the self-reported progress information.

PPC is a metric of LPS [4], which measures the reliability of the planning process. PPC was not explicitly measured in the current study, but based on the results in case 4, it is likely that even a 100% PPC can be achieved with a relatively low presence. Existing metrics still consider the events between the start and finish times of a task (CPM and LBMS) or within a weekly plan assignment (PPC) as being a black box. More recent metrics, such as the construction flow index [95], are also based on the start and finish dates and thus operate with the same limitations. Together with the tracking system, the thesis proposes more accurate metrics (PI and PP) for daily production planning and control of site activities.

5.6.3 Contribution to material management practices [73]

The thesis also contributes to material management practices in construction by developing and demonstrating a method to manage kit-based logistics management using an indoor real-time tracking system to monitor both material and worker flows. More specifically, the tracking method is developed to integrate material kit and labor tracking for a kitting logistics solution in a scalable way by measuring the uninterrupted presence of both labor and material kits.

One of the specific contributions to the methods based on the presence of materials and workers in work locations is that the developed method does not require manual observation or watching through camera videos to understand the process. For example, using camera monitoring and manual observations, Tetik et al. [33] pointed out that the effects of random factors may be large due to a relatively small dataset. The current method does not rely on manual analysis and thus is scalable to large datasets, which will help avoid random factors.

In addition to methodological development, the contribution to material management practices in construction lies in the introduction and demonstration of several KPIs to evaluate the effectiveness of the kitting solution. When the kitting process works in an optimal way, it fulfills the following requirements: (1) kits only go to the right apartment, (2) kits only move in once and out once, and (3) workers are present in the planned work location with the correct kit. The results from case 5 have shown that none of the requirements were met in the project we tested, so the implemented kitting practice was far from optimal. Calculating these KPIs in real time could allow management to find the root causes of problems and to continuously improve material logistic solutions. Such a system could be seen as a digital twin of the logistics process and could drive improvement in the way that Sacks et al. [96] proposed in their recent paper on digital twin construction.

5.7 Managerial implications [9,22,73]

The managerial implications of this thesis are presented from the perspectives of the presence time of workers in work locations, task progress, and monitoring of labor and material flows. The share of time workers is 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 [18]. Therefore, decreasing 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 serve as a proxy for waste. Management can evaluate the amount of worksite presence before and after lean or digital interventions. For example, material logistics has traditionally been shown to be a major contributor to waste [97]. If the project implements just-in-time logistics, how much it would impact the presence of workers in work locations could be evaluated. Similarly, although many digital tools have been proposed in construction, the construction industry still suffers from low productivity. New digital tools should pass the test to determine whether they increase the share of time workers can spend in work locations or not. In addition, real-time evaluation is important. 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. The assumption of the current study, 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.

For the implementation of a real-time indoor positioning system to detect the task progress in construction, the proposed framework and methods have several important implications for construction management. (1) The task-level progress tracking system can provide just-in-time information on task start and finish times. In cases where obvious errors occur from workers' self-report records, the tracking data are a good alternative and can be automatically obtained. (2) The proposed evaluation metrics for the tasks, such as PPs and PIs, can be used to automatically raise alarms for on-site management problems in real time, thus supporting efforts to decrease waste. For instance, a low level of PPs or PIs of a certain task should be given more managerial attention on-site.

The study found that the task "self-entered progress information" from five tasks was subject to manual errors. The automated data collection for tracking in real time the task start and finish times could help avoid inaccuracy and reduce the need for resources to collect control data from construction production systems. The real-time tracking system could be an alternative for traditional human-based observations and inspections to report task progress. In the current study, the concept developed for the real-time tracking of workers and the progress of tasks satisfied the accuracy requirements in most tracked tasks. There is also the potential to improve the system by adding notification features and asking whether the worker has started a task after an uninterrupted presence has been detected, rather than simply letting a worker manually enter the task start and finish dates.

For the implementation of a real-time indoor positioning system to monitor both labor and material kit flows, the proposed tracking application framework also has some notable managerial implications. First, the proposed system and KPIs can help site managers understand how well the applied kitting solution performs. For instance, the disparity from the optimal situation quantified by NM can be used to indicate the amount of time when workers are present without any materials. Managers can use the method and KPIs when reallocating working resources to places where the kitting practice appears to have the most challenges. For example, in case 5, apartment A8 was found to be the most complex work location with the highest NM and kit-moving times, which should urge the site managers in this case to pay special attention to the task progress in apartment A8. Faulty amounts or kinds of materials for that apartment likely explained these issues. Second, for logistics providers, the automated detected timestamps of kit delivery and removal in/out from the work locations, and the value difference between TMA and TMD, can provide useful information about the correctness and punctuality of kit deliveries. If TMA is equal to TMD, then all assigned material kits have been correctly placed in the apartments, and no other material kits are needed for replacement. Logistics providers can use the information on kit delivery and removal to estimate approximate kit usage using cycle times in each work location. They can also estimate the right quantity and correct size of kits to be delivered to the assigned apartment. Based on real-time data logistics, providers can dynamically update kit delivery plans and executions to the site [18].

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

Furthermore, when it comes to digital techniques and innovation in construction, it is painfully common from many previous cases that despite a substantial number of successful pilots and tests, not many of them are scaled-up or potentially commercialized. Therefore, the current research aims at connecting existing knowledge of workers, work processes and technology in construction, providing a “good enough” monitoring system which overcomes issues such as high expenses (e.g., cameras and AI) or impossibility to scale (e.g., manually observation). For the purposes of operations management in construction, the system strives for balancing between high precision with steep costs and easy setups with manual recordings, and it is still acceptable in terms of implementation. In addition, the proposed system does not require any markings of workers’ identity, which contributes to more efficient site management with lower resistance from the workers and unions.

5.8 Limitations

The limitations of the research should be noted here, including constraints of implementation, identification of task progress, and material kits in work locations.

For the implementation of the indoor positioning system, the key limitation was that Raspberry Pi requires power supply and connectivity for each monitoring device. Connectivity issues could be resolved by adding a 4G dongle to each gateway, and one of the case studies (case 1) had a wireless network (WiFi) installed on site. The availability of power constrained how many locations gateways could be placed because temporary power was always not available inside buildings. Using a power bank or backup battery would not be feasible due to high maintenance efforts. This affected the locations that could be monitored. In all projects, entrances and exits to each floor had temporary power, which is probably also the case for most construction projects, because temporary power is typically connected via stairways. The availability of power supply caused differences among the case studies. Sparser gateway placement strategies of cases 2 and 3 led to smaller coverage of the system, which had to be resolved through heuristics. The need for heuristics was much lower in cases 1, 4, and 5, where power could be arranged in most of the apartments where the tasks were conducted. In future hardware development, these limitations could be addressed by preparing lightweight gateways that have only the minimum functionality required by the system. Such light gateways could be powered by a battery for the whole period of the indoor construction phase, in contrast with Raspberry Pi, which is essentially a minicomputer with much more functionality than is required in this simple use case. Connectivity was not a big problem in the selected cases, but it could be improved by developing the gateway function as a mesh network [98].

For the proposed method to detect task progress using the indoor positioning system in construction, one of the limitations is the inaccurate identification of the correct duration range for some tasks. Specifically, (1) task schedules are still needed to determine the first task in every workflow or to detect a task switch when there is no absence between two tasks done by the same worker; (2) with this method, it is not possible to distinguish between several tasks conducted by the same person unless using a threshold time range until the next presence appears (in case 4, it is set for 4 hours). In future studies, proposals can be made to place beacons to monitor the movement of materials that the tasks need to use so that more accurate identification of task switching can be defined according to the interactions of tracked workers and materials. (3) In the selected case, because the workplaces were small (bathrooms) and the dependencies between tasks were technical, it is reasonable to assume that the successor task could not begin before the predecessor ended. Without technical dependencies, it may not be easy to determine the correct task that should be conducted. (4) In the validation process, a small number of tasks were found to not match the workers' self-reported records very well. In future research, the system could ask for verification of the start and finish times from workers or site managers to clarify ambiguities.

For the proposed method to evaluate the effectiveness of kit-based material management practice, some limitations of the method should also be noted. One of the main limitations of this method may be the identification issues of materials and kits. According to the real-time tracking system used in this case, which showed a relatively good level of coverage (97.1%) and accuracy (88.4%), the results were generally satisfactory for workers and material timestamps to reduce resource flows in jobsites. It was not possible to determine the presence of specific materials in the kits, however, because beacons to monitor the kits were placed in case 5. In future studies, suggestions can be to develop additional features such as sending notifications to workers for simple confirmation of their current activities (such as waiting for materials, idle status, etc.) when the TMA degree appears to decrease during the day. With this feature, sorting out all uninterrupted worker presences to look for time durations could be avoided, which hinders the effectiveness of the kitting solution. Future studies can also learn actual reasons from workers' direct confirmations. Another limitation is that one beacon for the A3 kit was lost on-site in case 5, so the NM periods may have contained times in which workers were actually with the A3 kit, thus making the actual NM lower. However, some indication of the effectiveness of the underlying kitting practice could still be obtained by evaluating the value of TMD and checking a worker's status with the correct material kits in an apartment (i.e., the designated kits). In future research, beacons should always be tagged with the material kits during the tracking periods.

Table 22 lists a summary of the limitations and the proposals for the research efforts to address the limitations in future.

Table 22. Summary of limitations and proposals for improvement in future studies.

Implementation	Connectivity	Developing mesh networks to improve gateway connectivity.
	Power Availability	Preparing lightweight gateways that have only the minimum functionality required by the system
Methods to detect task progress	Need for task schedule to determine the first task	Integrating vision-based monitoring technology to determine the first task
	Difficult to distinguish between tasks unless using a threshold time	Placing additional beacons to study movement of task required materials for better identification of task switching
	Validate task presence with self-reported records	Developing the system to ask for verification of the start and finish times from workers or site managers to clarify ambiguities
Methods to evaluate the effectiveness of kit-based material management practice	identification issues of materials and kits	Developing additional features such as sending notifications to workers for simple confirmation of their current activities when the TMA appears to decrease during the day
	Lost beacons	Ensuring beacons always tagged with the material kits during the tracking periods

6. Conclusion

The conclusion of the thesis is summarized as threefold. First, this thesis has illustrated how a real-time tracking system based on BLE technology can be implemented in different types of indoor construction projects, more specifically in apartment plumbing renovation, residential buildings, and office buildings (research question 1). 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 (research question 2). When exploring the presence in work locations for the tracked workers in the projects, several threshold value times were introduced to identify the uninterrupted presence, which would be a necessary but not sufficient condition for value-added work. Through this method, PIs at the project level can be calculated from system data. Pis in all tested case projects ranged between 16.5% (case 5) and 35.5% (case 3) (at a threshold value of 10 minutes), which matches previous studies in which value-added time was evaluated and the data were collected manually. Therefore, the study suggests that uninterrupted presence can be calculated with the proposed low-cost system in real time.

Second, the thesis has demonstrated how the proposed BLE technology-based real-time tracking system can be implemented in construction sites to detect task start and finish times based on dependencies and task schedules (research question 3). The automated detection of progress information was validated against the workers' self-report data. In case 4, where the method of task progress detection was applied for 12 selected tasks in carpenter, tiling, and painting work trades, only an average of 34.42% of presence was needed to complete the tasks based on task PIs, and up to 66.17% of the task schedule could be compressed if the optimal workflow was reached, which shows great improvement potential in construction planning and control. Task-level PIs indicate the presence level required to achieve the actual duration, while presence-to-plan ratios indicate the presence level required to achieve the planned duration and capacities to compress the schedule. This information provides new insights that could contribute to establishing better workflows from lean interventions in construction.

Third, the thesis has also illustrated how the proposed real-time tracking system could be applied to the automated detection and analysis of time-matching levels of material kits and workers based on their uninterrupted presence. New KPIs were developed that can be measured in real time and offered opportunities to improve material and labor flows for kitting logistics solutions based on the proposed metrics (research question 4). The study found that notable durations occurred in work locations in which workers were without kits on-site. The variability of these durations in different places should be noted for managing kitting solution practices. The current method works by revealing the observed problems of kitting practices in real time, thus providing lean intervention opportunities for material–labor-related tasks on-site. Users can also evaluate the effectiveness of kitting practices in work locations based on the metrics introduced in this thesis.

Overall, this thesis suggests that a real-time tracking system based on BLE technology can be applied in construction projects for indoor positioning purposes and uninterrupted presence analysis. From the research perspective, it becomes possible to measure the impact of construction management or digitalization interventions on the long-term presence of workers and materials 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 the productivity impacts of delays.

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