Intelligent Construction Site (ICONS) Project Final Report

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1. Introduction

Intelligent Construction Site (iCONS) research project was initiated because there was a growing concern that real-time data about production is not available in construction industry. Data was collected in the form of schedule updates, where typically the superintendent or project engineer walked the site and manually inspected the status of tasks and entered the results into a scheduling system. The most modern technologies in use at the start of the project included mobile applications that the workers could use to enter the status of their tasks. However, there were concerns about the quality of data entered. The workers only could access tasks that were planned in the system. From previous results in lean construction research we know that the most important thing is the flow between the value-adding activities. If the flow is poor, the production system has waste. The mobile approaches could not accurately record waste because they were based on manual input and the workers do not necessarily understand which activities are wasteful. iCONS was initiated because of these concerns to evaluate technologies which could give real-time data in more objective fashion and allow the managers, dedicated data analysts or AI-based systems to detect patterns in the data.

From the beginning, the project attracted significant interest both in Finland and internationally. The Finnish consortium which partially funded the research included three contractors Fira, Skanska and YIT and a process consultant Carina Solutions, which offered services mainly to marine industry in the beginning of the project but increased their offering to construction projects during the project. Three software companies Movenium, eRENT and Trimble participated in the consortium with the aim of using the results to expand their business. Elisa represented teleoperators in the consortium. International partner network included contractors from China, Brazil and United States who offered their feedback on requirements and Tianjin University, Stanford University and University of Campinas from Brazil. Technion Israel Institute of Technology had conducted some prior work with similar scope and organized a workshop in Finland to kick off the iCONS research work.

The consortium decided to focus on tracking labor, material and equipment during interior construction phase. Interior construction is typically the hardest construction phase to control because there are no easy ways to understand what is going on. Construction projects are typically large and contain hundreds of rooms. Materials and tools get lost and there was a sense that a lot of waste occurs during this phase.

After sharpening the focus of the project to interior construction phase, the research group started to develop a prototype technology. The state-of-the-art was reviewed and after some debate, the technology solution was chosen to be a Bluetooth Low Energy beacon solution connected to Raspberry Pi gateways. After prototype development, the iCONS system was implemented on four construction sites where volunteering workers and some materials and equipment were tracked for a period of few months. The results were analyzed and used to define required improvements to the prototype, a mobile app to use the information for management purposes and ways to analyze the data to provide important information. The technology was then developed further and identified problems were corrected and three additional case studies in Finland and three case studies internationally were run to evaluate the global potential of the solution.

The results of the project exceeded expectations. Implementing indoor positioning in construction sites proved to be cost-efficient with low maintenance requirements even with the prototype solution. The data allowed the researchers to measure waste on site by looking at how long workers are able to be present in work locations and by comparing the actual movements of workers to plans. Results related to material tracking confirmed previous hypotheses about inefficiencies related to material logistics. It turned out that in the case projects only around 30% of worker time was value adding and typical tracked materials had to be moved six times before they were consumed. The results can be calculated in real time to give a measure of efficiency of the work site. This allows management to evaluate the impact of different lean or digital interventions on efficiency or even predict problems before they happen. For the first time construction production can be managed with real-time data!

This final report describes the requirements from Finnish consortium and international partners. Then we detail the technical solution and its development. Case projects and their results are introduced next including the learnings from each case study. Company perspective to results is given next by Fira, who started to aggressively digitalize their operations as the result of this project. Finally, the results are compared to goals and future development directions are introduced, including several new research efforts that are already ongoing.

2. Requirements for the iCONS system

We interviewed the consortium companies and companies from each of the collaborating countries: China (3 companies), United States / California (3 companies), Brazil (2 companies). All companies identified the lack of real-time information for management as a key topic. The current manual practice has too long delay between occurred fact and action and real-time Key Performance Indicators are lacking. It is unclear why delays are occurring. International companies emphasized safety aspects, especially related to automated safety warnings and to control access in hazardous areas. Figure 1 summarizes the international requirements.

Relevant Requirements	Brazil		USA			China		
	Rossi	Brookfield	Irvine	Turner	Suffolk	Mag	JCM	China State
1. Safety Management	-	-	-	Correlating productivity rates with safety incidents	Control access in hazardous areas	-	Cameras on the crane to monitor on-site activities	ICONS decision-making for safety warnings
2. Process information, productivity and waste	Agility in information; Equipments' inefficiency	Big delay between the occurred fact and actions	Lack of real-time information	Forecasting and root causes analysis; Delay analysis	Common understanding of the work to be done	Multi-project environment	Having control panels to read the RFID	Weekly schedule to ensure the performance and to track the process
3. Material logistics	-	-	Materials are really on site, and how quickly they are consumed	Materials can't block the path and must keep crew productive	Real-time material tracking	-	Warehouse management to place the material	-
4. Location-based information on pull basis	Subcontractors' performance	-	Accuracy on location and number of hours spent	Where workers are and what tasks they are doing	More accuracy on locations	BIM collects the info to ICONS	-	-
5. Project Management	More accuracy on construction time	Reduction of construction time and costs	More informed conversations with subcontractors	Transparency Schedule compression	Manpower control; Helping subcontractors to improve productivity	"Delicacy management" to know the planned and the actual	-	Poor at managing subcontractor's schedule
6. System and user interface	Offline use Native language	Offline use Native language	-	Visual management environment; Offline use	Offline use	Open API, easy to be transferred to other system	Easy to understand for local engineer	-

Figure 1: International requirements

The requirements can be summarized as follows: (Olivieri et al. 2016)

Safety management: highlighting work in hazardous areas and risks related to interactions between equipment and labour; increasing safety motivates workers to accept tracking devices.

Process information, productivity and waste: tracking movements of the workers on construction site, and controlling how much time workers spend in one location, analysing productivity rates and waste of time, analysing what has been completed in each location, linking images automatically to locations.

Material logistics: controlling the logistics of off-site and on-site materials.

Location-based information on pull basis: giving information to superintendents, foremen and workers in real-time based on the location they are in.

Both the Finnish consortium and the international partners thought that the indoor construction phase of buildings is the most problematic area for real-time information. It is relatively easy to observe in real time the erection of structure because it is possible to see all the workers from the site office, but anything that cannot be seen because it is inside or off-site is a problem. Therefore it was decided that the technology developed in the project would focus on real-time location of assets in an indoor construction environment.

The requirements were summarized in Figure 2 which was accepted as the starting point of development of the iCONS system.

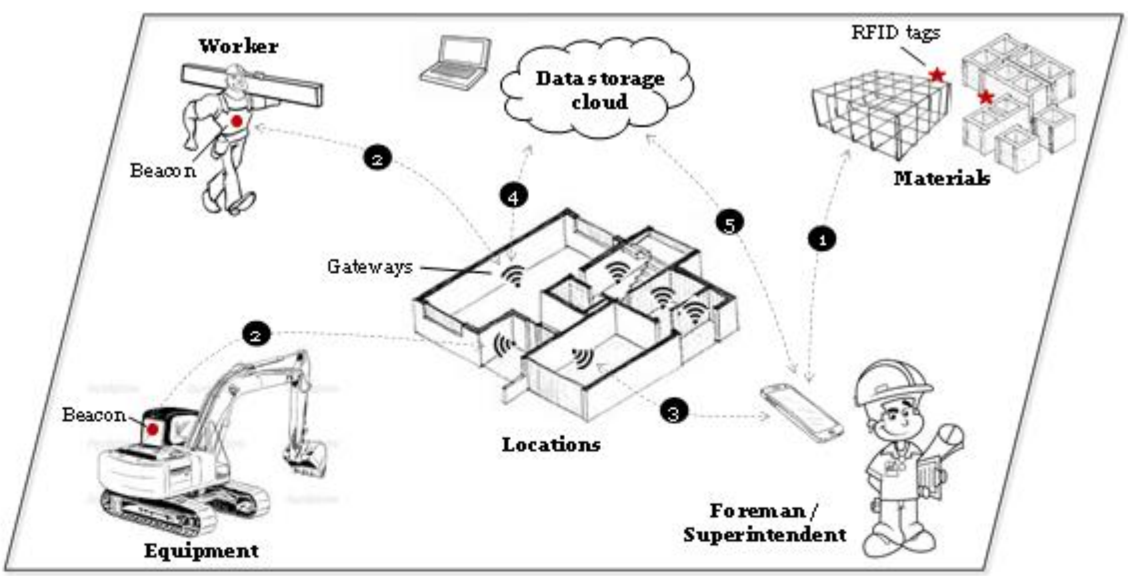

Figure 2: Initial vision of the system fulfilling the requirements (Olivieri et al. 2016)

3. Technical iCONS system development

System architecture overview:

The iCONS system architecture comprises of three separate parts: a) Bluetooth Low Energy (BLE) beacon b) Gateway c) Cloud. In iCONS system the data is produced by beacons, transferred by gateways and consumed and analyzed in the cloud. Figure 3 shows the overview of the system architecture. In the following, a comprehensive explanation about these parts is given.

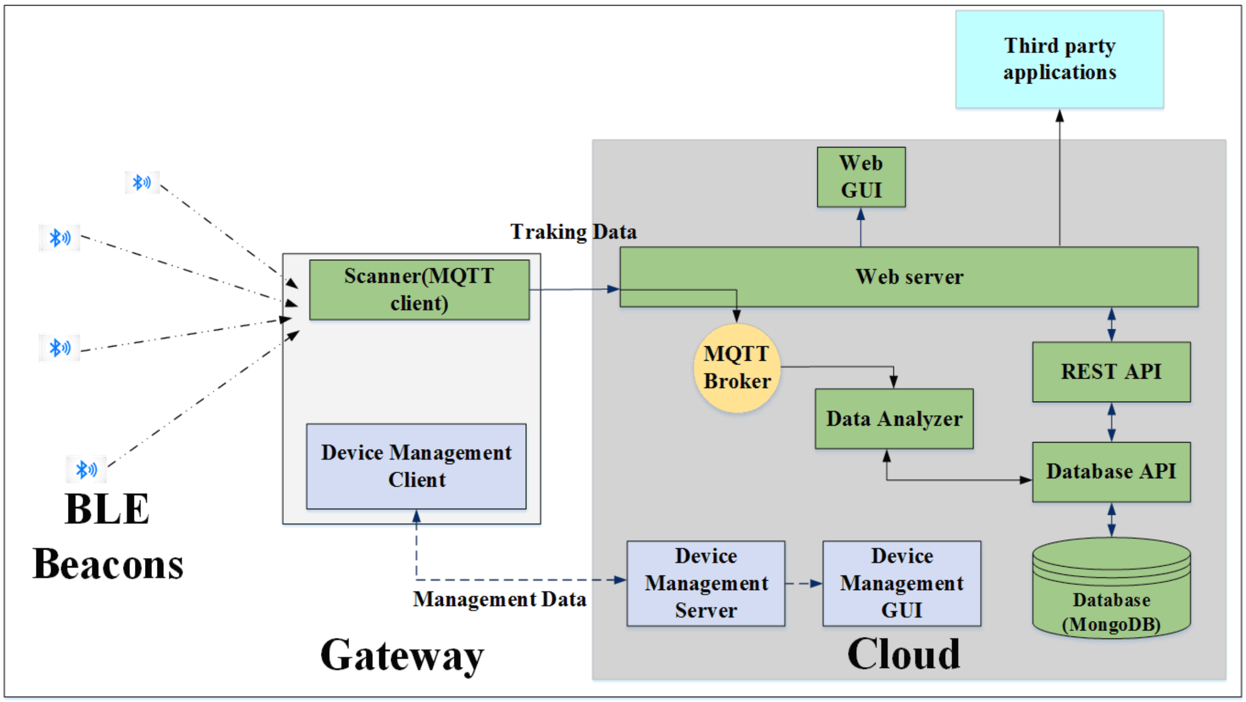

Figure 3: Overview of solution architecture of the iCONS

BLE Beacons:

Beacons use Bluetooth Low Energy (BLE) radio technology to transmit beacon broadcast. The technology is designed and marketed by the Bluetooth Special Interest Group (SIG). Beacon concept is very simple and can be compared to the lighthouse by which the light is emitted and can be seen by anybody in the vicinity; beacons also broadcast a signal to the surrounding environment and any compatible device can capture that. Beacons are operating in the unlicensed 2.4 GHz ISM (industrial, scientific and medical) band. Having said that, Bluetooth share this bands with other technologies like WiFi, cordless phones, microwaves and etc.

Type of beacon protocols:

1) iBeacon: Apple developed iBeacon and it is widely supported and simple to implement.
2) Eddystone: Google developed Eddystone and it is open format and flexible with Google products. Eddystone protocol is able to transmit three different frame-type. These formats are:
    a) URL: is used to transmit a URL to the devices.
    b) TLM: is used to send sensor and administrative data for instance, temperature, battery level or accelerometer data.
    c) UID: is a 16 digit string that is utilized to identify the individual beacon.
3) Altbeacon: Radius Networks developed Altbeacon in order to solve the problems related to favouring one vendor to others. This protocol is open source and interoperable with other mobile operating platforms.
4) Geobeacon: Tecno-World developed Geobeacon for GeoCaching applications. This protocol is also open source and compatible with other mobile operating platforms.

In our project, we have utilized beacons with iBeacon protocol. The beacons with this protocol periodically transmit the following information:

- Universally Unique Identifier (UUID): a 16 byte string used to identify the owner or vendor a large group of related beacons.
- Major: a 2 byte string used to identify a smaller subset of beacons within the larger group. For instance, all beacons in the a building can have the same major number.
- Minor: a 2 byte string used to identify individual beacons. For instance, a beacon in the third floor of a building.
- Tx power: is used to determine the proximity from the beacon.

Beside the above mentioned information that are packed in the beacon packets, MAC (media access control) address also exists and we have used each beacon's MAC address in order to identify the individual beacons. In addition, we have filtered out beacons from other manufacturers by using UUID. Figure 4 shows the beacons that have been used in iCONS project.

Figure 4: Two types of beacons used in iCONS.

Battery life: The battery life time varies from a manufacturer to another and depends on what specification is in use. The transmission power can be adjusted in the beacons, which in turn, increase the transmission range. The higher the transmission power the lower the battery life. In addition to transmission power, broadcasting interval is another factor that affects the battery life, meaning that with more frequent transmission interval the battery life will be shorter.

Gateways:

Gateways are the intermediate intermediary entity between the beacons and the cloud. The gateways continuously scan and collect the signals from beacons in the vicinity. After collecting signals, data is transmitted to the cloud. In order to send the data to cloud, Internet connectivity is required for the gateways. In most of the projects, the WiFi has been the major connectivity technology whenever it was possible in the construct sites; otherwise the cellular technology was provided by using cellular dongles. As Figure 5 shows, we used Raspberry Pi3 which is a generic single-board computer with Linux operating system.

Figure 5: Raspberry pi is used as a gateway.

We have two separate data flows between gateway and the cloud: a) tracking data flow and b) management data flow. These two data flows are completely independent from each other.

a) Tracking Data: As the name implies, all tracking data are exchanged through that. A scanning module written in Python language collects the data from nearby beacons and transmit them to the cloud in predefined configurable intervals. As the protocol for transmitting tracking data, we used Message Queueing Telemetry Transport (MQTT).

b) Management data: In order to manage gateways, we have used LightweightM2M or simply LWM2M protocol from the Open Mobile Alliance (OMA). This protocol is designed for sensor networks and the needs of machine-to-machine environments. LWM2M allows users remotely perform task, run diagnostics, and run applications and device management tasks on their IoT (Internet of Things) embedded devices.

We used Leshan (https://www.eclipse.org/leshan/) for implementing device management protocol in iCONS (Figure 6). Leshan is an open source code written in Java. We developed the interface part of LWM2M server and client. The LWM2M client is located in the gateways and Server sides in the cloud. Figure 6 shows a screenshot of the device management web page of the iCONS. Using this tool, user is able to control gateways in the remote area without physical access to them. For instance, user can change the name of a gateway, change the location name of a gateway, obtain the public and private IP address and etc.

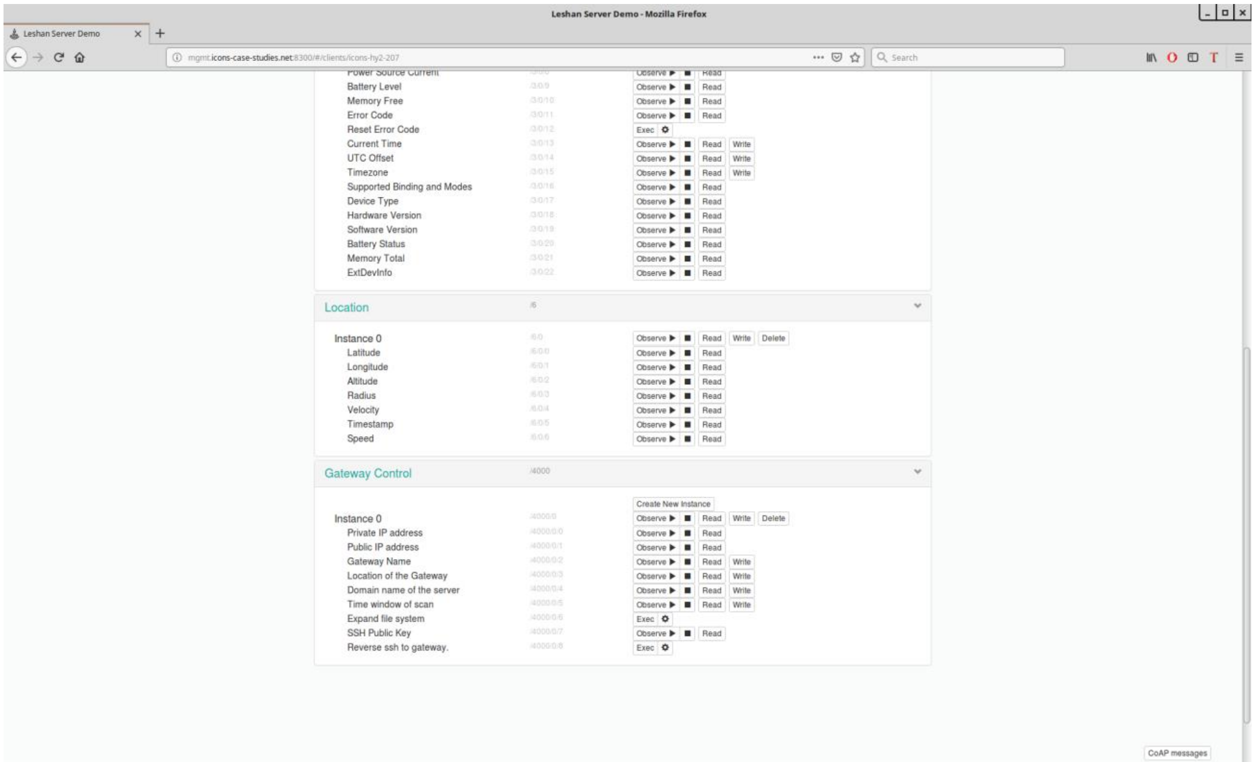

Figure 6: Screenshot from device management (Leshan) web page.

Cloud:

The main part of iCONS system resides in the cloud and the main functionalities are performed in it. Similar to the gateway, there are two separate data flows in the cloud, which are tracking data and management data. Management part includes the LWM2M server which connects to the LWM2M clients installed in the gateways. The tracking section in the cloud is the central part of the iCONS system and its modules are detailed in the following:

MQTT protocol:

MQTT is a publish- subscribe based messaging protocol developed by IBM. It is extremely simple and lightweight messaging protocol designed for constrained IoT and M2M devices under high latency and unreliable network. In MQTT, normally large number of devices send their information to a single destination (cloud) where the data can be analyzed, interpreted and forwarded. The cloud hosts an MQTT broker that is an intermediate entity lies between the devices (gateways in our system) and the other devices that consume that information (Data analyzer in our system). In other word, broker is a bridge that connects the data of the gateways to the Data analyzer module in the cloud.

Web Server:

We used NGINX as the web server, which is a free, open source and high performance HTTP server and reverse proxy. In iCONS project, all of the incoming requests and also MQTT's incoming data are performed by NGINX. For more information about NGINX, please refer to this link: https://www.nginx.com .

Database:

We used MongoDB which is a document-oriented database and classified as NoSQL database program. MongoDB utilizes JSON-based documents. For more information, refer to the following link: https://www.mongodb.com/

Data analyzer:

The main brain of the iCONS system lies in this module. Data analyzer module is responsible for analyzing the incoming data, filter out the redundancy data, and store the data in database. Data analyzer subscribes to the broker for incoming data from the gateways. In this way, all of the date are immediately directed to the Data analyzer. After analyzing, processing and filtering the data is stored in the database using Database-API module. Database-API module is responsible for fetching data from database and storing data in the database. So no other module can directly access to the database.

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

The method for position location used in this prototype is based on Cell of Origin method. In this method, the position location of a beacon is determined by the nearest gateway that can hear its signal. This means that if the signal of a beacon is received by several gateways in the vicinity, the gateway that receives the strongest signal is chosen as a beacon's location. This functionality is executed in the Data Analyzer module. This module compares the RSSI of the beacons and assigns the location of the beacon to a gateway which receives the strongest signal. The RSSI is used as a measure of closeness to the gateways. This value is highly dynamic in the indoor environment and keeps changing due to multi-path propagation of the wireless signal resulted from refraction and reflection in the surrounding environment. To overcome this problem and smoothing out the RSSI values, we utilized an array of N recent RSSI values of each beacon in each gateway. Storing a new value in the array pushes the oldest one out. By averaging the last N value of RSSI, the outlier values are removed from the RSSI values and flickering problem is addressed. The algorithm is shown in the Figure 7.

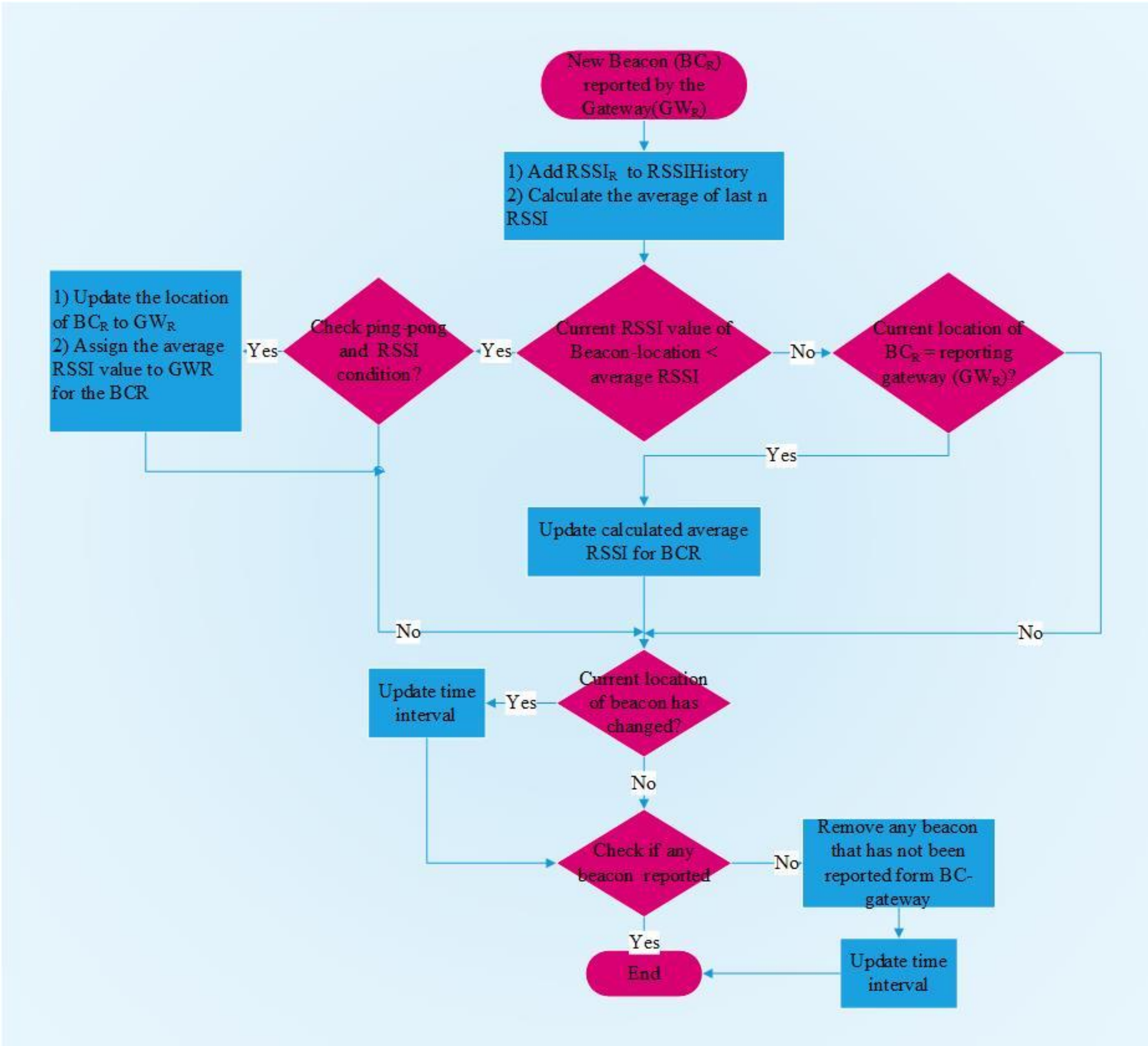

Figure 7: Data analyzer algorithm used in iCONS.

The location of each gateway is known, therefore by knowing the fact that beacon belongs to a gateway, the approximate location of the beacon is determined. As the Figure 2 shows, there are two data flows between gateways and cloud: a) tracking data which is used for location of the beacons and b) management data which is used for managing, parameter settings and configuring gateways via Graphical User Interface (GUI) of the Device Management module. These two planes of data are independent from one another.

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

Mobile application

During the project a mobile Android application was developed. The application was intended to server the following purposes:

1. Indicate where particular workers, pieces of equipment or materials (also referred as assets) currently reside
2. For a selected location, display current assets in that location
3. Show movement history of the assets within the construction site

The mobile application obtains data from the server in real time. It displays the real-time position of the current user and latest known data (including current location and its timestamp) about all tracked assets. The application obtains historical data about asset movement from the server and provides convenient filtering by name, location and time interval for retrieving required data.

In order to use the mobile application, a user must log in to the system using the assigned username and password. Then the user must associate a Bluetooth beacon that the user (in this case the worker) is carrying to his account. This allows the application to always indicate the current position of the worker's beacon - and at the same time the location of the worker. The user can search for other assets by name or Bluetooth tag identifier, see where those assets currently reside and check a detailed history of the movement of the assets. For example, a user may search for a piece of equipment (A), select a period of time, e.g. last week and instantly see in which rooms and for how long A was placed. As another example, one can see where a particular worker e.g. an electrician spent his time working time and how much time was spent in different locations across the construction site. A few examples of the iCONS mobile application user interface are shown in Figure 8.

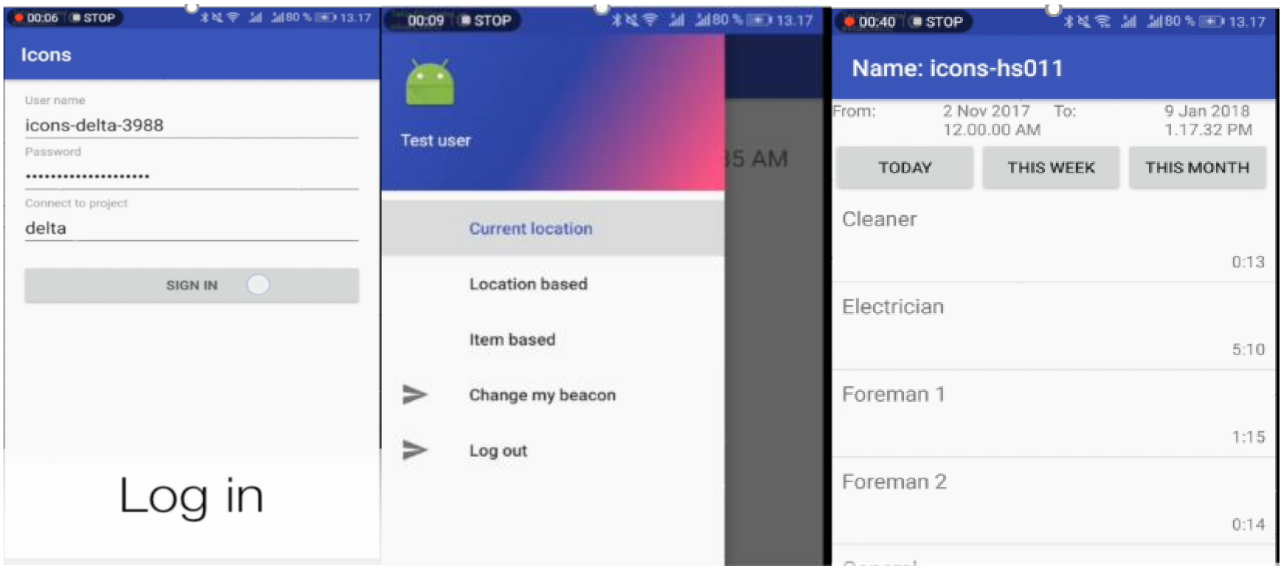

Figure 8: iCONS mobile application user interface

Beacons with accelerometer sensors:

We are at the moment testing the new type of beacons with embedded accelerometer sensor in the construction sites. The aim is to infer the activity type of the workers by analyzing the accelerometer data collected through gateways (Figure 9). The activity recognition can be achieved by using machine learning techniques. This work is in the progress in a follow-up research project.

Figure 9: Beacons with accelerometer sensors used by the workers for activity recognition.

4. Case Study test results

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

4.1 First round of ICONS onsite implementation (2017-2018)

4.1.1 Fira renovation project with Kiilto materials 2017 (address: : Tykistökapteenintie 2, Helsinki)

Overview of the project

The building is constructed in 1970 and it is an apartment building. The location of the building is in Lehtisaari, (Helsinki); address: Tykistökapteenintie 2. The building contains 3 floors and the base floor contains 20 garages and pipe channel. 16 apartments are in the first and the second floors. The first floor contains also pool department, heat distribution room, main switchboard, laundry room, drying room, club room, storages and refrigerating store. Building contains 4 stairwells (A, B, C, D). Figure 10 shows an exterior picture of the project.

Figure 10. Onsite entry and storage area

The contract of Fira comprised the renovation of bathrooms, toilets and HVAC systems. Also, some modification works were executed in common spaces such as the pool department. Every bathroom and toilet were renovated. Water and sewer systems were renewed. Vertical sewer lines were replaced in already existing shafts but new shafts were built for vertical water pipe lines Exhaust valves were be renewed and some of them also had to be rearranged. Electric and telecommunications systems were renewed and the routes utilized the new water pipe shafts/routes. Kiilto participated in the project by delivering materials from their warehouse to the jobsite. The materials were mainly bathroom materials for the renovation project.

iCONS system set-up

The tracking period was from Aug.28 to October 13, 2017. The simplified section of the jobsite is illustrated in figure 11. Work locations were one or two bedroom apartments which were separated with concrete walls and slabs. The total square area was around 1100 square meters per floor.

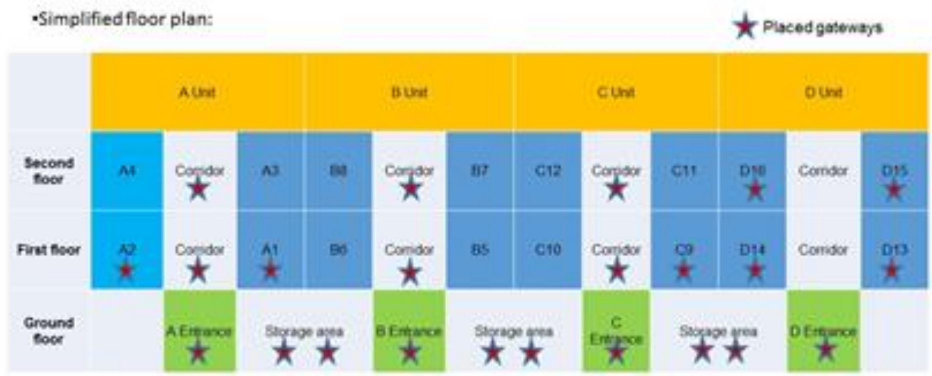

Figure 11. Fira real-time tracking case study schematic plan

In this project, we tried to place as many gateways as possible, wherever there was available power, to ensure that a majority of the apartments would be covered individually by gateways. Gateways were placed at the following areas: (1) entrance areas (four gateways), (2) storage areas (six gateways), (3) stairwells/corridors between apartments (six gateways), and (4) inside of apartments (seven gateways). Due to the power limitation, though some of the apartments had a dedicated gateway, in some floors, there would be a situation where one gateway in the corridor served two apartments. Instruction was sent to workers and foremen (Figure 12) after they gave us their consents of our tracking process. The gateways were installed on construction lamps because they were able to supply sufficient power (Figure 13).

Figure 12. Onsite instruction for Foremen and workers

Figure 13. Gateways attached on the construction lamp onsite

Results/data analysis

The case study was the first feasibility test of iCONS system in a real project. The collected data indicated time and location information of workers onsite. The case focused initially mostly on the feasibility of the system but the data was analyzed later together with other case studies to evaluate worker presence in work locations.

In the beginning the patterns of data for individual workers were investigated. Two attributes were compared: on-site time detected and on-site time per day total. The first one indicates the accumulated minutes of the day that the foreman/workers was detected onsite (by any gateway); the latter one refers to the total time from the first detected time to the last detected time of the day that the foreman/workers was on site. Based on the results in Figures 14 and 15, we determined that either the foremen and workers spent a substantial amount of time off-site or the system suffered from accuracy problems.

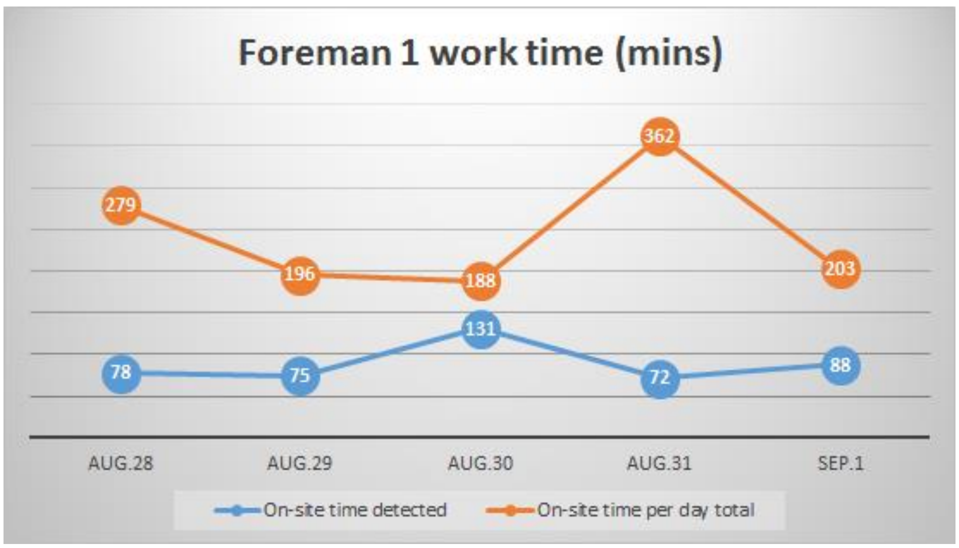

Figure 14: Foreman 1 work time on-site

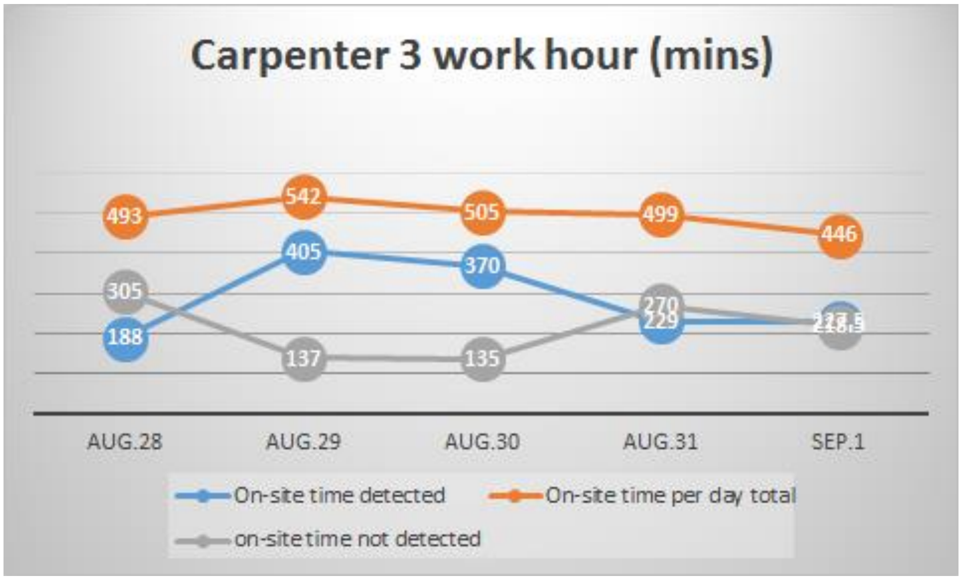

Figure 14: Carpenter work time result from Aug 28-Sep.1, 2017

Key learnings

Since the case study was among the first case studies that were scheduled in Finland, our main focus was to test whether iCONS real-time tracking system could function properly in real construction projects on site. The goal of the case study was primarily to look into the functionality of the system and try to get some general tracking information out of the iCONS data. Some key learning points for further development included:

(1) The Bluetooth Low Energy technology based tracking system that iCONS project applied was implemented in the residential renovation project, and the tracking data were successfully downloaded from the cloud, thus allowing data analysis of workers' movements onsite.

(2) The raw data included some amount of "flickering" where workers would alternate between two locations and it was unclear where the worker was really located.

(3) Time accumulation would be a good start for data analysis of the tracking, to obtain a rough estimation of the workers' daily working time length. However, more detailed information should be addressed to serve the purpose of operations management onsite.

(4) Power supply was one of the key limitations onsite when the implementation process took place. It was difficult to find a stable place to attach gateway with power supply without workers disturbing the installation

4.1.2 YIT office renovation

Overview of the project

The second case study was an office building renovation in central Helsinki, Finland. YIT was the General Contractor in this project. The building has seven floors (approximately 2800 square meters per floor) above ground and one floor underground. At the time of the case study, each floor was an open space. It was the first time where iCONS was implemented in an open space office project.

iCONS system set-up

The tracking period was from September 21 to November 30, 2017. 13 beacons were assigned to workers and 21 gateways in total were placed on site. During the tracking period, several visits were paid to the jobsite for system set-up and maintenance inspection. The researchers were moving around in the building trying to record their real movements for work simulation, which is part of accuracy testing for the data validation. Because of lack of power supply, each floor had only a few gateways so some areas were where no gateway could detect the beacon. The simplified floor plan is presented in figure 15. The entrance gateways at the front gate and back gate were regarded as non-work related places because they were next to a storage area while the others were regarded as gateways in work-related places. Figure 16 shows the overall construction environment and Figure 17 shows an example of gateway installation at temporary power.

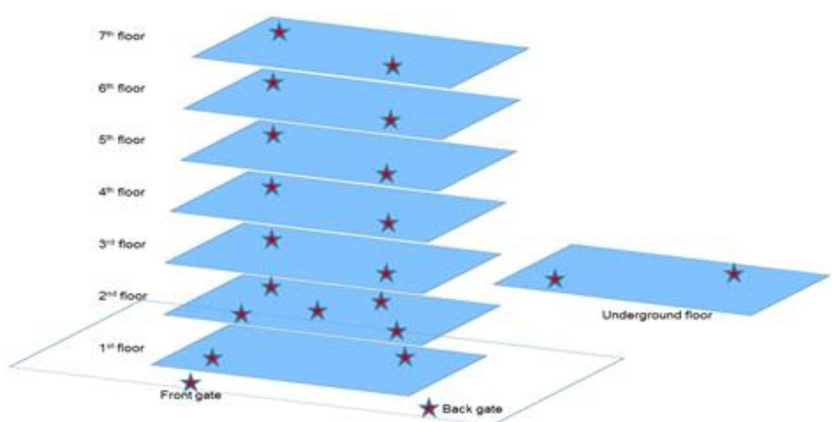

Figure 15. YIT real-time tracking case study floor plan

Figure 16. On-site construction environment of YIT open space office project

Figure 17. Gateway attached on the power supply onsite

Results/data analysis

In this case we reviewed data quality and accuracy in detail. Unlike the first Fira case where many gateways were able to be installed onsite, this case had the limitation of power supply in large open areas each floor, thus leaving spaces where no gateway could detect the beacons' signals. This led to our investigation for system accuracy and coverage of iCONS set-up.

Data accuracy was evaluated by comparing the tracking data in the system to the data self-reported by the researchers. Because the gateway placement strategies in both projects were different, the process was able to provide valuable information on how tracking device placement impacts accuracy. To evaluate data coverage more deeply, we analyzed the researchers' and workers' location data in both cases. The "coverage ratio" was defined as the proportion of time the beacon was actually detected out of the total operational time of the day. The total operational time of a worker was the time from the first detection of a beacon on site on a day to the last detection on the same day. The coverage ratio indicates how well the system is covering the job site operations. .

The result showed for YIT case based on researchers' movement data, during the period time of 91 minutes, only 37 minutes were matched with the ground-truth data (the researcher own record). This shows that the placement of gateways is a crucial part of implementation. If the gateways cannot be installed to cover the whole site, some heuristic rules are required. Table 1 shows the coverage level in both cases.

Table 1. Coverage ratios in Fira and YIT cases compared with that of a 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. Fira: Plumbing renovation	66072	98191	67.3%	72.1%
Case 2. YIT: Office open space renovation	47242	154482	30.6%	45.1%

Goal of the case study and key learnings from the cases

The goal of the case study was to examine the feasibility of iCONS real-time tracking system on another construction type -- office open space project. Besides obtaining the individual workers' time analysis, we started to explore the data quality from the raw dataset, which would be beneficial for the future development. Some key learning points were the following:

(1) Both data accuracy and coverage estimation from the raw dataset showed a relatively unsatisfying performance of the system at that time; therefore, there was a need to develop some heuristics to improve the coverage ratio.

(2) Gateway placement can substantially affect the coverage ratios so finding a good placement strategy for each project is critical to ensure the quality of data.

4.1.3 Carina

Overview of the project

The case of CarinaFour Company was located in Turku area of Finland where one factory producing prefabricated cabins for marine industry and one warehouse were chosen for the project. The company is working on materials which are pre-processed in the warehouse and then transported to factory. This was among the first case studies of iCONS system implementation, and the goal was to examine the feasibility of iCONS system set-up in logistics.

iCONS system set-up

The simplified floor plan for the case study is illustrated in figure 18. Racks of materials were waiting to be transported in warehouse area (warehouse circle) and then trucks shipped them to the material waiting area of factory (factory waiting area circle). After waiting time, the materials were moved inside the factory to be processed (work area circle). By placing gateways near the circles and attaching beacons in racks that carried construction materials onsite (figure 19), time stamp information of materials movement as well as their worker in charge could be recorded. With the help of timestamps, racks of material processing time, waiting time and associated worker time spent information become available.

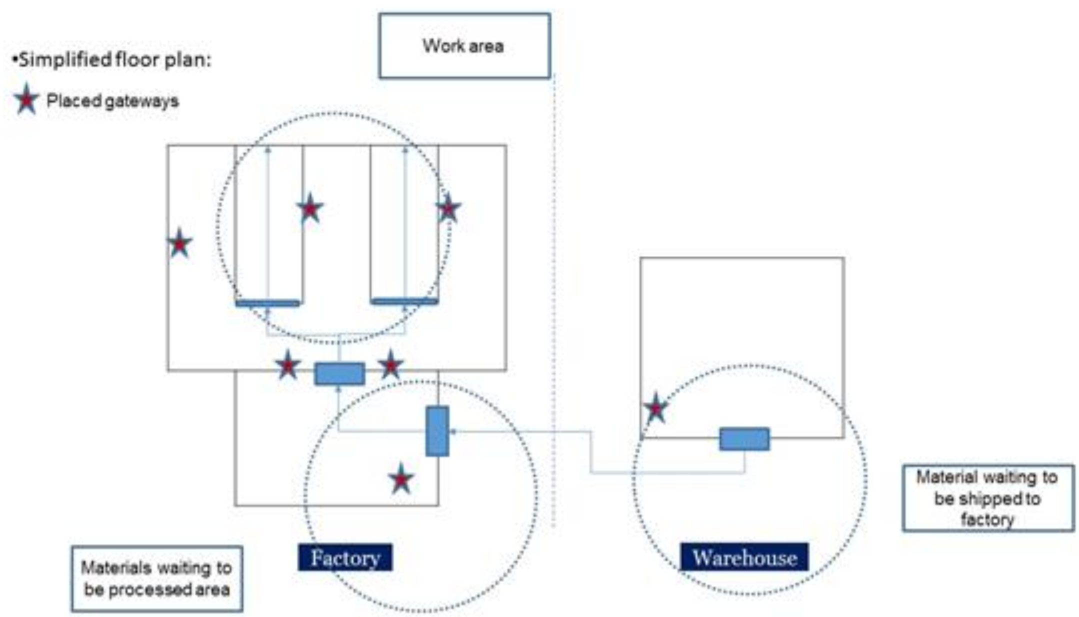

Figure 18 CarinaFour real-time tracking case study floor plan

Figure 19 Racks of materials on-site

Results/data analysis

The case study aimed to track the racks of materials from warehouse to factory where they are to be processed. It was possible to obtain general information of logistics flows and workers daily time spent onsite. In figure 20 the process time is defined as the time period from when the racks entered the factory until the racks left the factory indicated by passing the gateways near the entrance/exit. It indicates the material process duration, which has the managerial implication for logistic flows. Figure 21 shows the work time of worker No.5 in factory during the tracking period. Combining the material and worker tracking could be used to indicate the value-adding progress.

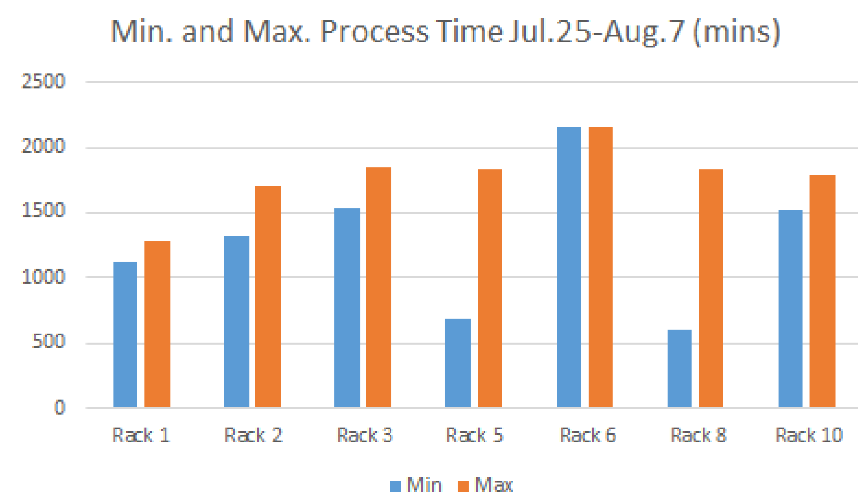

Figure 20. Material processing time result July 25-Aug 7

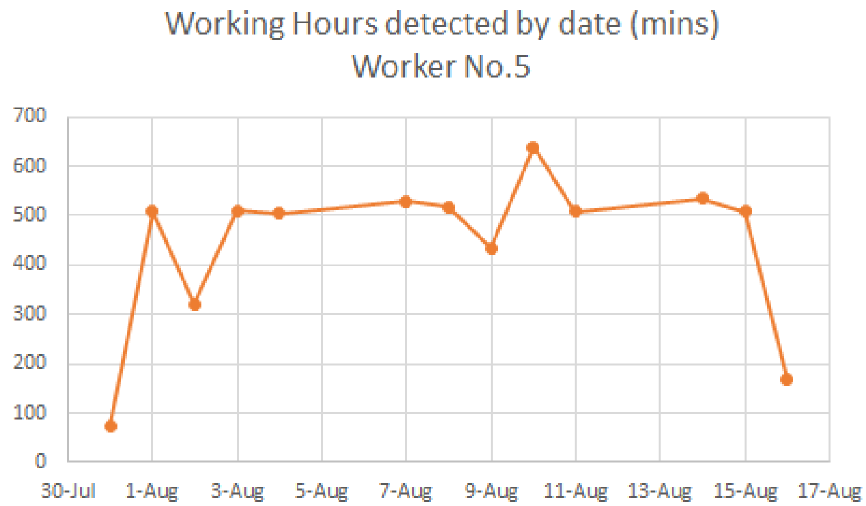

Figure 21. Workers working time in factory by date

Key learnings from the case

The case study primarily tracked different racks of materials onsite, aiming to provide general information of the logistic flows onsite in factory. The iCONS real-time tracking was successfully implemented on material and worker tracking in factory. Some key learning points for future studies were as follows:

(1) The case study was the first one that includes both material and worker tracking. This provided valuable guidance for future data analysis to look into the case how workers are using the material under the same tracking scheme.

(2) Logistic flows can be detected by iCONS tracking system, thus making it possible for material providers (e.g. Kiilto) to follow their material status easily.

4.1.4 Skanska residential project

Overview of the project and iCONS system set-up

The case study was a new residential building project in Helsinki, Finland. The simplified floor plan is presented in figure 22. The building had three stairwells and a construction site office. Each stairwell had five floors. Gateways were placed on each floor of stairwells A and B as well as in the office area. Two gateways were categorized as non-work-related areas, one in the site office and one in the entry area of B & C building) while all other gateways serve as work-related areas. We focused on A & B buildings because the construction work in building C had not been started at the time of the case study. This case has similarities to Fira case (plumbing renovation) because in both cases, the testbeds were set in residential buildings where rooms were divided by concrete walls.

However, the different strategies of gateway placements in those two case studies can provide valuable information of how and where we can install gateways to achieve a optimal result.

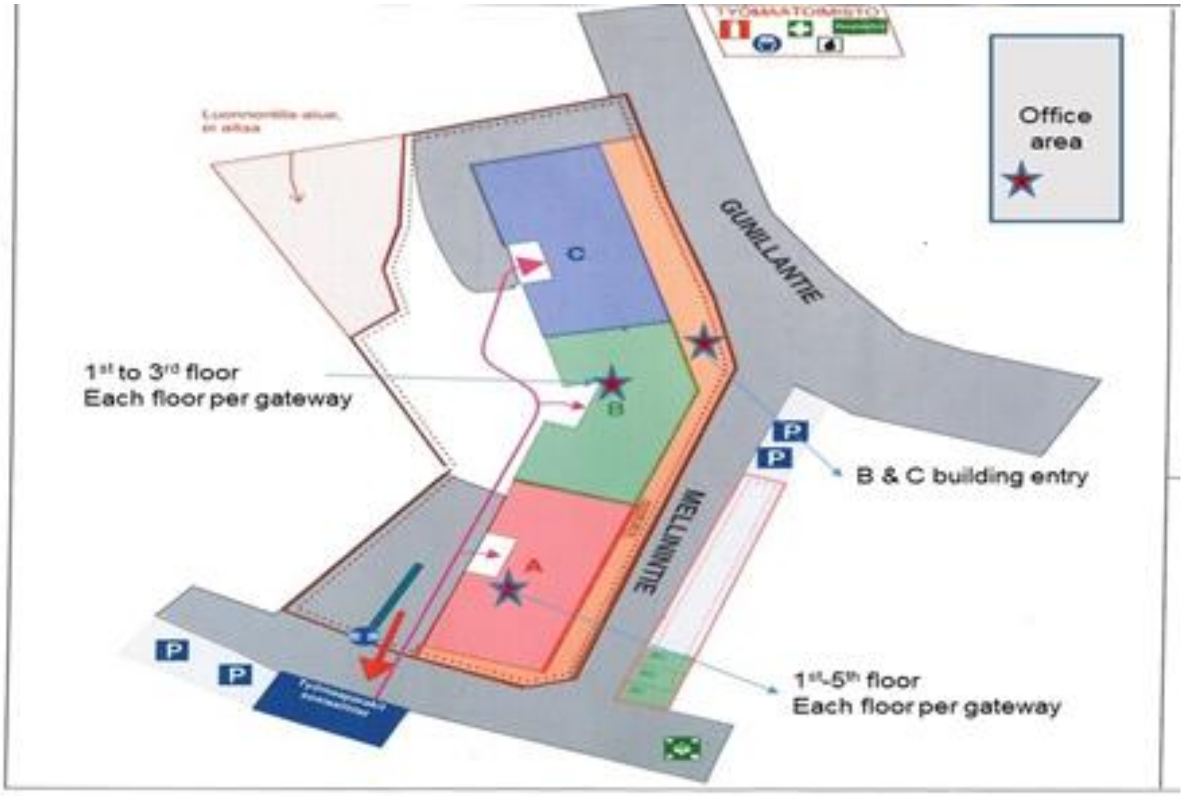

Figure 22. Skanska case study gateway placement floor plan

The tracking period was from October 18, 2017 to January 31, 2018. 11 workers agreed to tracking and 10 gateways in total were installed onsite. Onsite conditions and gateway installations are shown in Figure 23. Similar data was collected and reported as for the other case studies.

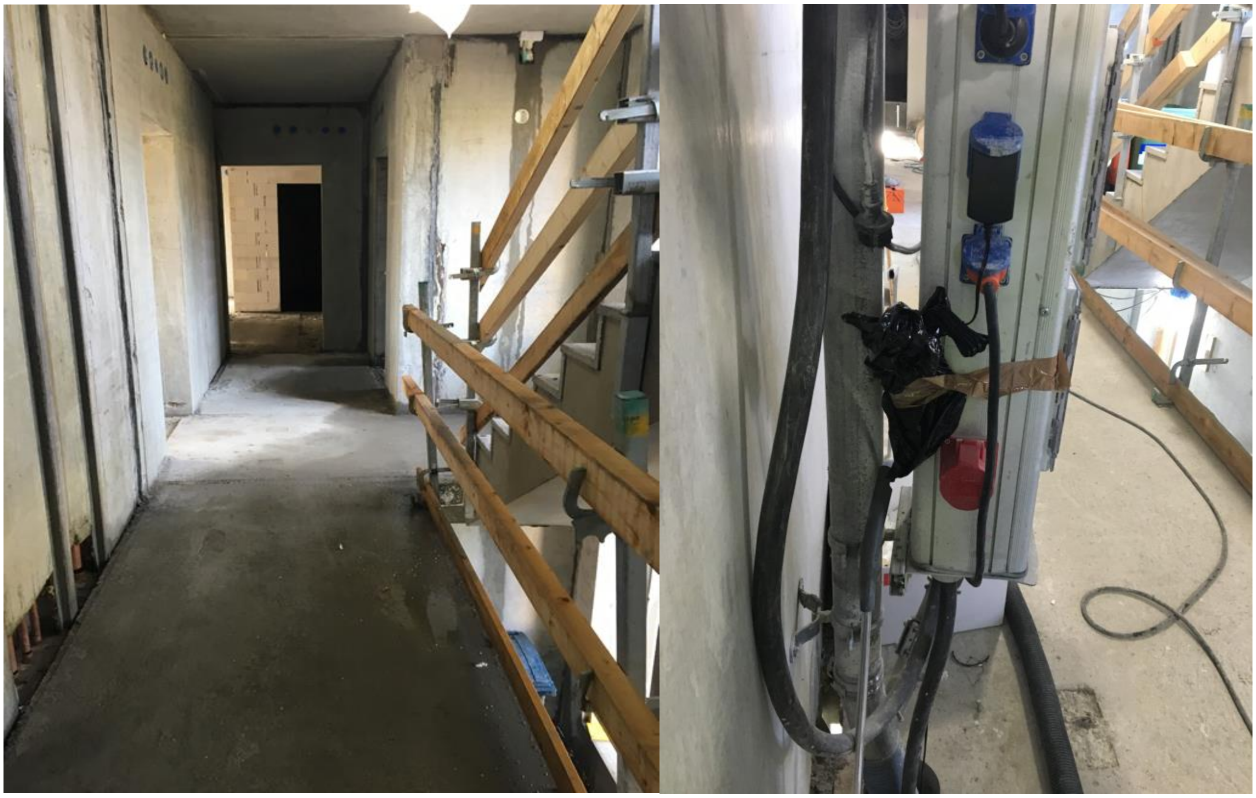

Figure 23 Onsite conditions (left) and gateway attached at the power supply each floor (right)

Heuristics development based on the first round of cases (Based on Zhao et al. in review)

Because we noticed that it is difficult to get 100% coverage of construction site with gateways, we decided to develop heuristics that would be able to figure out if the asset is still inside the building even if it is not detected by the tracking platform. Workers can be undetected by the system if they are really away from site or because the gateways are not able to detect them either due to lack of coverage or short-term problem with interior environment interfering with transmission. The rules we implemented were quite simple:

1) If the asset is last seen at an exit gateway and then disappears from the system, then we assume that the asset has been off-site
2) If the asset is last seen at an interior gateway, it is probably still in the building but not detected by the system.

To implement this heuristic, the only additional information required is to label each gateway as either an entrance or an exit gateway. After introduction of these heuristics, the worker's coverage ratios increased in all project as indicated by table 2 below.

Table 2. The workers' coverage ratios before and after heuristics (from Zhao et al. in review)

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

Uninterrupted presence analysis (Zhao et al. in review)

With improved coverage, it was possible to estimate the proportion of worker presence in work locations. Because we noticed a lot of movement between work locations in the data, we calculated how often the workers are able to stay in work locations for longer durations of time without interruptions. We called this uninterrupted presence (Zhao et al. in review). The argument was that if the worker just briefly visits a location, they cannot be doing valuable work. Therefore at least a period of 5 or 10 minutes without interruptions is required before anything useful could happen. It turned out that most of the periods were short 0 or 1 minute stays as indicated in table 3 below.

In the table, the threshold time is the number of minutes the worker needs to stay in a work location before the time interval is included in the calculation. The presence index was calculated both including the heuristics and without the heuristics. The presence indices varied between 24.5 and 35.5% which matches closely with previous research results about value-adding time. Therefore, a 10 minute threshold for uninterrupted presence could be used as a metric for real-time was analysis.

Table 3 Presence indexes at work with different threshold values (time in minutes; excluding data of site managers) (from Zhao et al. in review)

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 Fira. 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 YIT. 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 Skanska. 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%

Key learnings for development

After the first set of case studies, the concepts of heuristics and threshold values were introduced to indicate the uninterrupted presence of workers at work locations Some key results are as follows:

(1) Though the raw dataset might show unsatisfying quality and coverage, it is possible to implement data analysis heuristics to enhance the results.

(2) Uninterrupted presence index can be used to evaluate the overall productivity of the project.

The first round of case studies led to the following recommendations for gateway placement:

Gateways should be placed:

(1) At each exit location;

(2) In any work location enclosed by concrete walls, such as apartments;

(3) In locations where it is possible to access other floors (stairwells, elevators);

(4) In open spaces at least every 30 meters.

4.2 Second round of iCONS implementation

After understanding the limitations of the system and required improvement measures, the second round of case studies was conducted in 2018 to (1) enhance the system detection measurement by minimizing the data flickering problem; (2) visualize the movement of workers and materials in a more intuitive way; (3) compare with schedule to validate iCONS tracking data.

System was developed between the cases by averaging the last N values of RSSI to remove any outlier values from the received signal strength indication values. This effectively addressed the flickering problem that was noticed in the first round of case studies. Additionally a mobile application for situational awareness was implemented. However, the workers and foremen were reluctant to implement it in the case studies. Therefore, we concentrated more on data collection and analysis.

4.2.1 Fira plumbing renovation project 2018

Overview of the project and iCONS system set-up

The second round of iCONS implementation with Fira was scheduled from March 8th to June 1st, 2018 another plumbing renovation project. It was a renovation project in residential building where 18 beacons were distributed to workers. Figure 24 shows the simplified floor plan and the location of gateways. We tried to place as many gateways as possible but due to power limitations onsite, we could place gateways mainly at the corridors of the stairwells or the construction lamps.

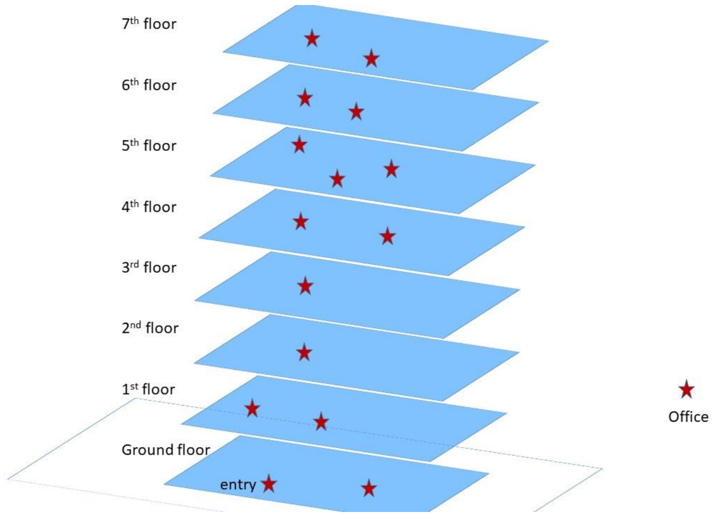

Figure 24. Simplified floor plan for Fira case study 2018

Results/data analysis

We estimated the project-level presence time of all tracked workers (Figure 25).

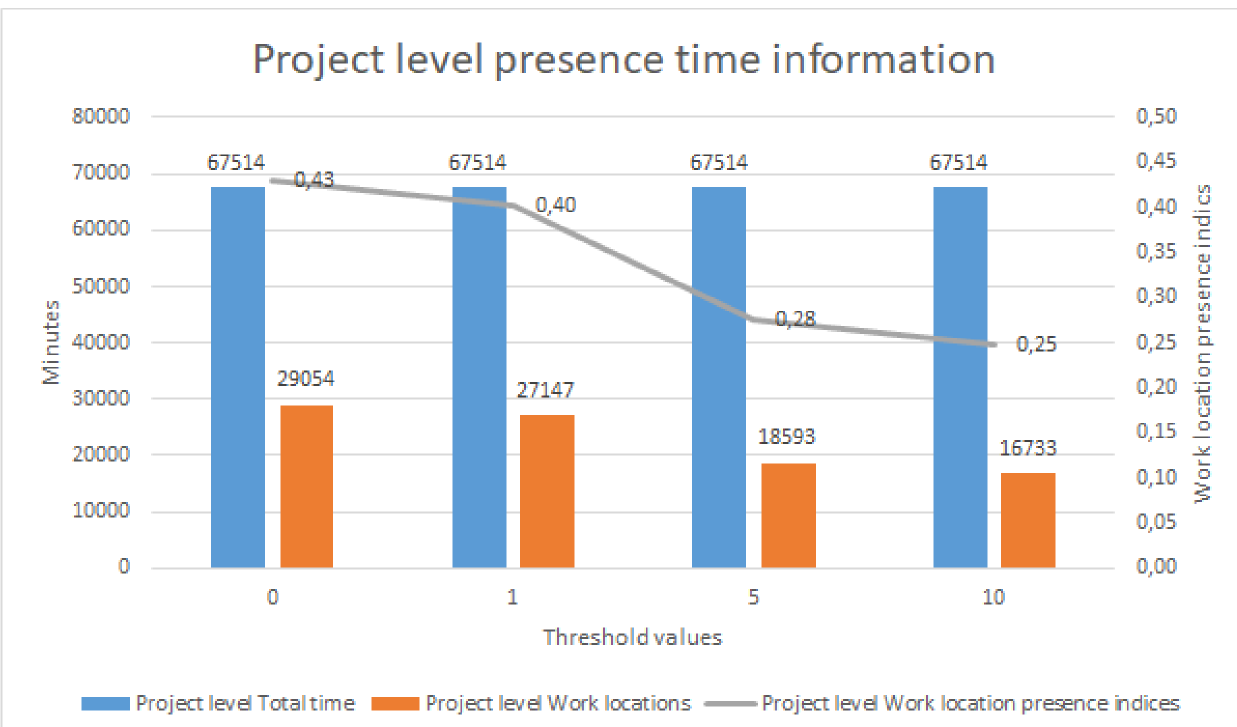

Figure 25. Project-level presence time information of Fira renovation project

Compared with the Fira case study in first round, the work location presence indices have dropped even though the gateway placement had lower density. With lower gateway density, we assumed higher work location presence because the workers have to move more in order to move to another work location and thus interrupt the stay in work location. Therefore, on project level, this project had a lower level of presence in work locations than the first project. The project was the first one tested in iCONS tracking system after its development of averaging signal strength for improving the data flickering issue.

4.2.2 YIT with Kiilto

Overview of the project and iCONS system set-up

The project involves YIT as a general construction contractor and Kiilto as a construction material provider. Kiilto had a warehouse in Vantaa and the jobsite was also in Vantaa. Killto needed to transport bathroom materials to the jobsite therefore we placed gateways in both locations. We assigned four beacons to four workers that are doing the bathroom work there and we attached around 100 beacons on bathroom material packages provided by Kiilto (figure XX).

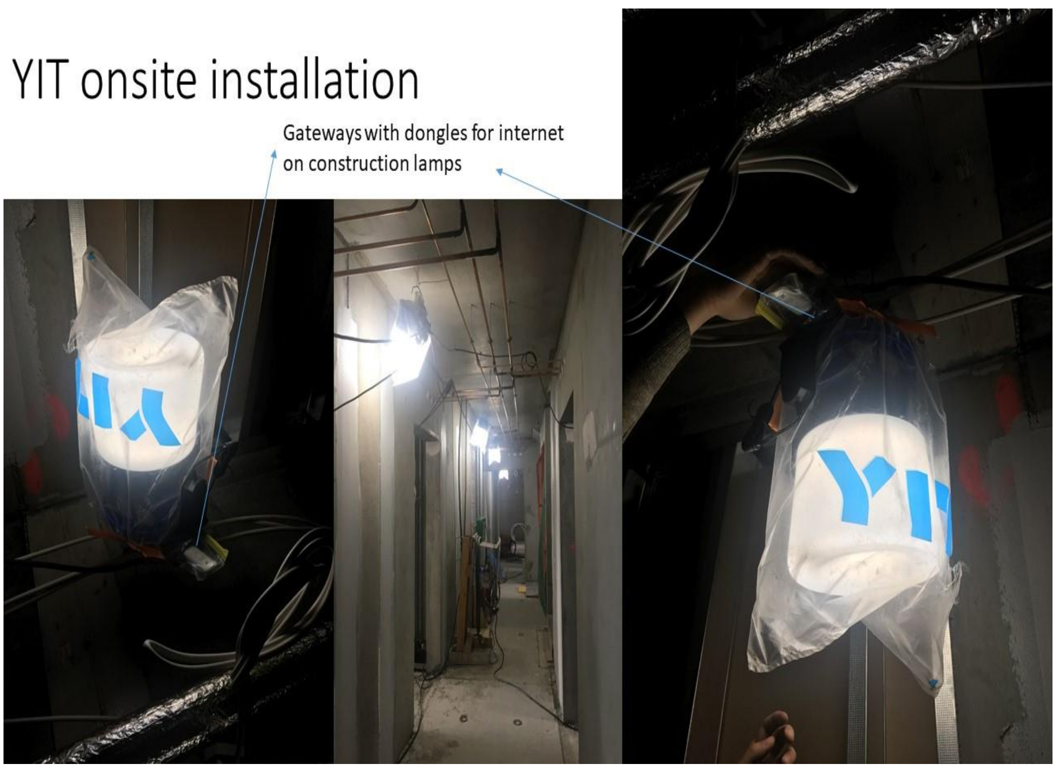

Figure 26. YIT jobsite iCONS system installation

Figure 27. Kiilto warehouse beacons set up on material packages

Compared to the material racks tracking in CarinaFour project, this case study focused more detailed in individual material packages to be delivered to the bathroom. The simplified floor plan is shown in Figure 28:

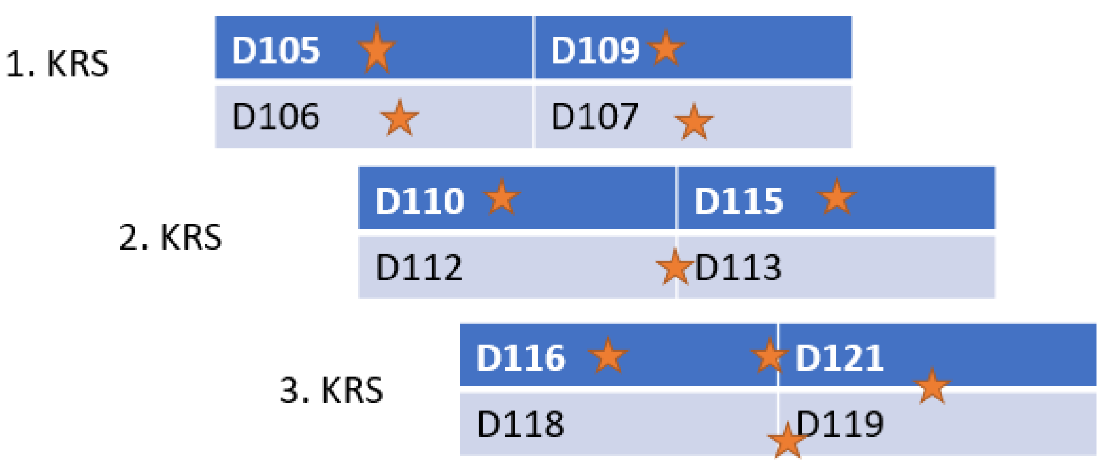

Figure 28. Floor plan with gateways marked at YIT jobsite

Results/data analysis

In this case, we tried to analyze the whole logistics chain of bathrooms by looking at material flow from the warehouse to the project site and by following the workers related to the materials. In examples below, we illustrate the results by visualizing the movement of four packages (corresponded to beacon No. 155, 156, 158 and 159) in figure 29 for illustration of the logistic flows from Kiilto warehouse to YIT jobsite (time window. September 21 to October 6).

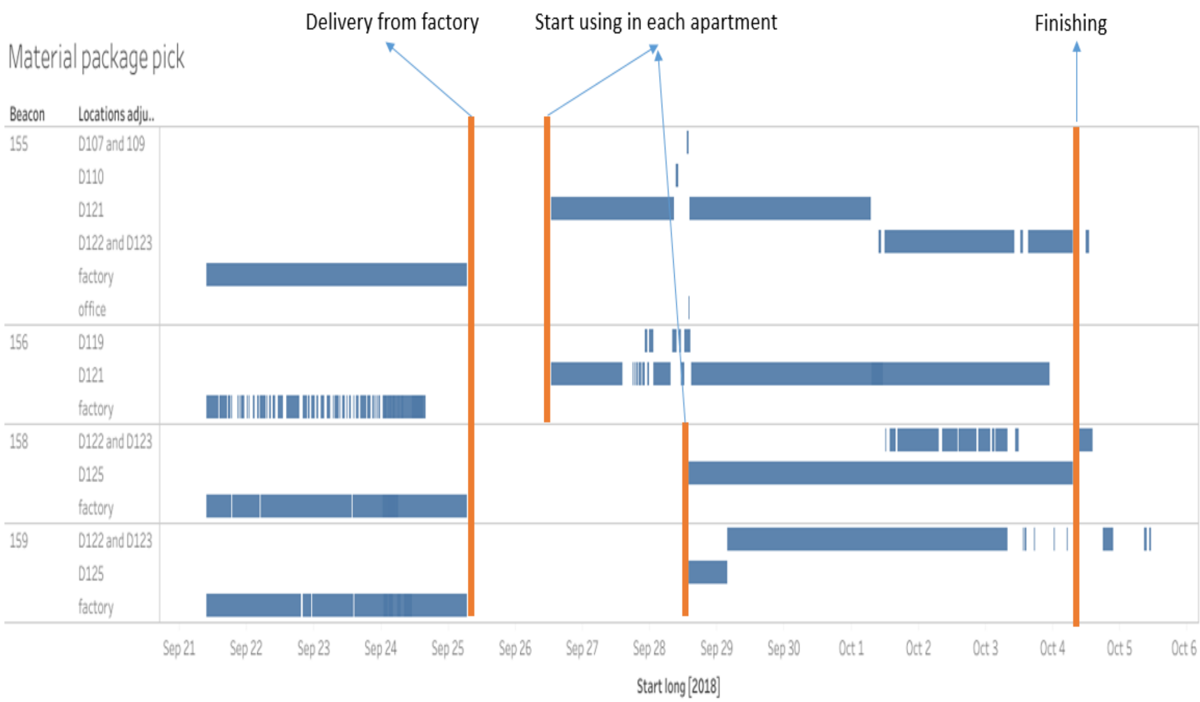

Figure 29. Logistic flows of four tracked material packages from warehouse to jobsite

We also tried to look at the case where workers and material packages were picked up together at a specific day. By visualizing both worker and material movement on October 17, 2018, we were hoping to see how in details the worker was using the material in the apartment. However, the visualization figure 30 showed a rather chaotic movement line for one worker (beacon 149) and three material packages (beacon 148, 176, and 198) that were meant to be used in apartment D113, 115 and 134, 135. We are currently working on additional analysis to figure out rules for complex interactions between labor, materials and planned schedule.

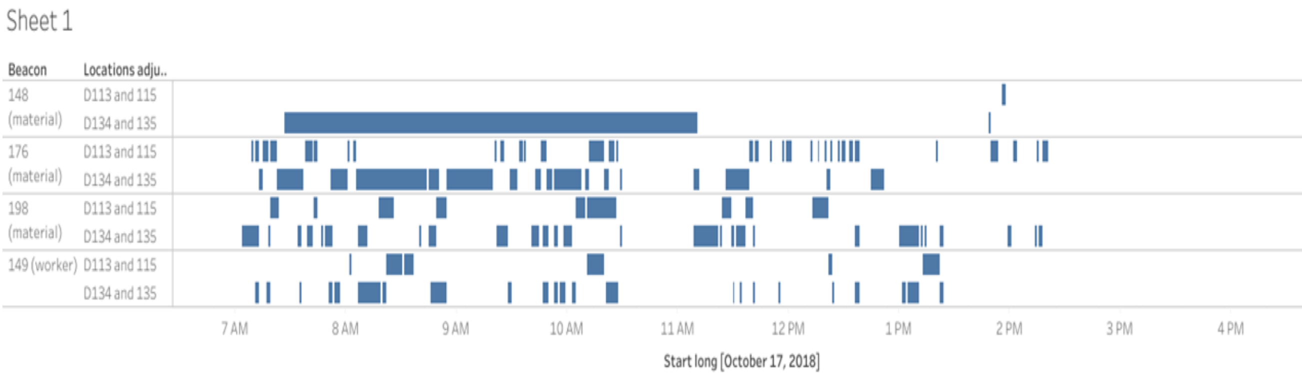

Figure 30. October 17. Worker No. 149 using material package No. 148, 176 and 149

Key learnings from the case

This case study aimed to provide a testbed for material package tracking in practice. It also provided the opportunity of observing how workers consume the material in the specific place by analyzing both workers and material packages at the same time and location. Some key learning points were as follows:

(1) For a single material package tracking, it is possible to obtain the time stamp information of the logistic flow from warehouse to the jobsite.

(2) However, just by visualizing movement of workers and material packages, it is hard to get systematic and logical knowledge about how the worker was actually using the material packages. In future, we need to come up with rules and heuristics to figure out what was going on based on interactions between labor and material. It is clear from the visualization that the rules can be complex.

4.2.3 Carina plumbing renovation project with ALU

Overview of the project and iCONS system set-up

The case study was a residential renovation project located in Helsinki. The material was delivered from an Assembly and Logistics Unit (ALU) which was located in Tuusula. The case study tracked both material boxes and workers in different work types including carpenters, plumbers, plasterers and bricklayers. The gateway placement covered each apartment onsite and the ALU (figure 31). Ten workers, two foremen and twenty material boxes were attached with beacons for tracking.

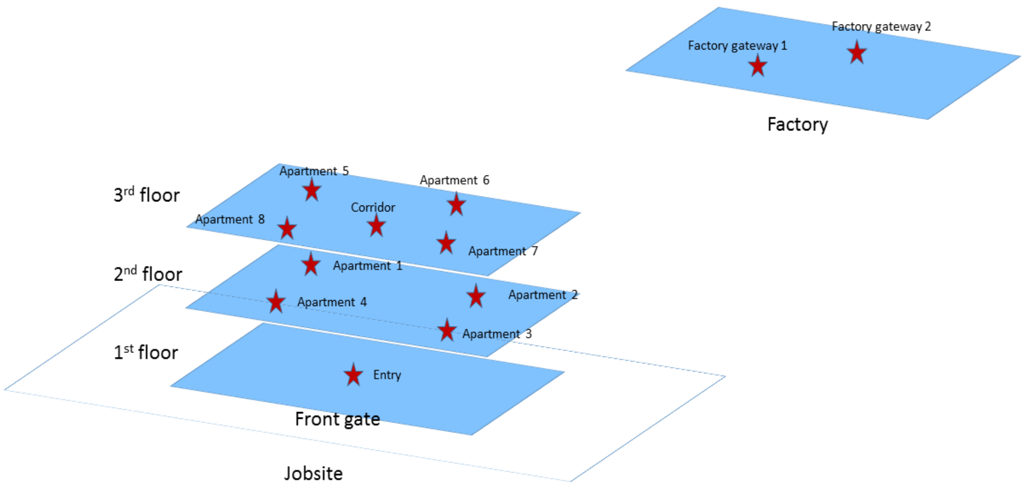

Figure 31. Simplified floor plan of gateway placement

Results/data analysis

In this case we evaluated the presence indices at work locations on different work types and the comparison time spent between workers' schedule and their tracking data from iCONS system (Figure 32).

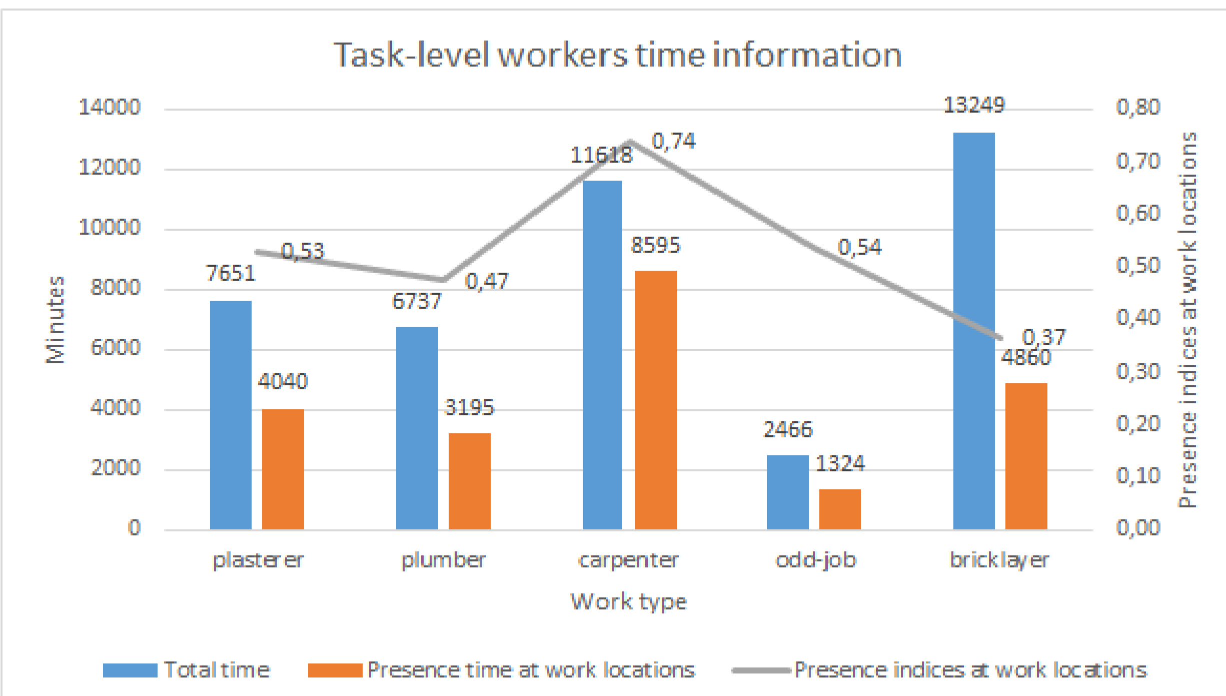

Figure 32. Time information of workers in different work type in the case study

We also tested relating the tracking data to schedules. In figure 33, the horizontal axis indicates the date and the vertical line indicates the apartment number associated with gateway numbers. Schedule can be used to determine if the workers spend time doing productive work in the correct locations. The method is to first interpret schedule on an individual worker level which can then be higlighted in the figure, depending on the level of detail of the schedule. For example, in the table, carpenter 1 is scheduled to work on June 7th in apartment a1,a2,a3,a4,a5 and a6 (all highlighted cells). Highlighted cell in the table means place and time according to the schedule, and number in it means the work minutes accumulated in that location for carpenter 1. For example, for June 7 carpenter 1 has worked 544 minutes at apartment a2 and it is right location according to his work schedule. Because the schedule did not indicate work separately for each carpenter but for all carpenters combined, there are many cells which contains 0 minute or little minutes for carpenter 1 in the scheduled time and place. It is possible that some other carpenter completed work there.

Carpenter 1	GW No.	Date	5	6	7	8	11	12	13	14	15	18	19	20	21	25	26	27
	32	a1																
	37	a2			544.0083													
	42	a3																
	36	a4																
	38	a5																
	39	a6																
	40	a7		0														
	43	a8																

Figure 33. Location-based presence time at work locations in schedule for carpenter 1

Key learnings

This case allowed us to examine the presence level of different work types onsite provided gateways installed in each apartment. We did the first tests trying to combine iCONS tracking data and worker's schedule. Some key learning point of the development:

(1) Comparing worker's schedule with iCONS system tracking data is difficult because the schedules are not generally on the level of individual worker. In future research, we need to compare all the workers of each contractor to their scheduled tasks.

4.3 International case studies

iCONS system has been supported and tested also in our partner countries: Peru, the Netherlands and China. Because of the easy and standardized procedures of system set-up together with inexpensive device requirement, the real-time tracking system was successfully implemented in each country.

4.3.1 Peru

Scope:

The project by the contractor consisted of the general maintenance of steel structures (23 Columns of 6m high, 442 Joists of 6m length, 28 Steel trusses of 26m of light and braces in general), the replacement of 4,396.00 m2 of current coverage by a TR-4 curve coverage, the front and rear enclosure by the manufacture and assembly of the corresponding structure. Finally, the installation of the ventilation system through 44 wind extractors and 4 air injectors. Figure 34 shows the schedule and 35 the floorplan with gateways indicated.

Location: Puente Piedra, Lima, Lima, Peru

SECTOR	5/11/2018	6/11/2018	7/11/2018	8/11/2018	9/11/2018	10/11/2018	11/11/2018	12/11/2018	13/11/2018	14/11/2018	15/11/2018	16/11/2018	17/11/2018	18/11/2018	19/11/2018	20/11/2018	21/11/2018	22/11/2018	23/11/2018
1																			
4																			
5																			

Figure 34: Gateway installation schedule

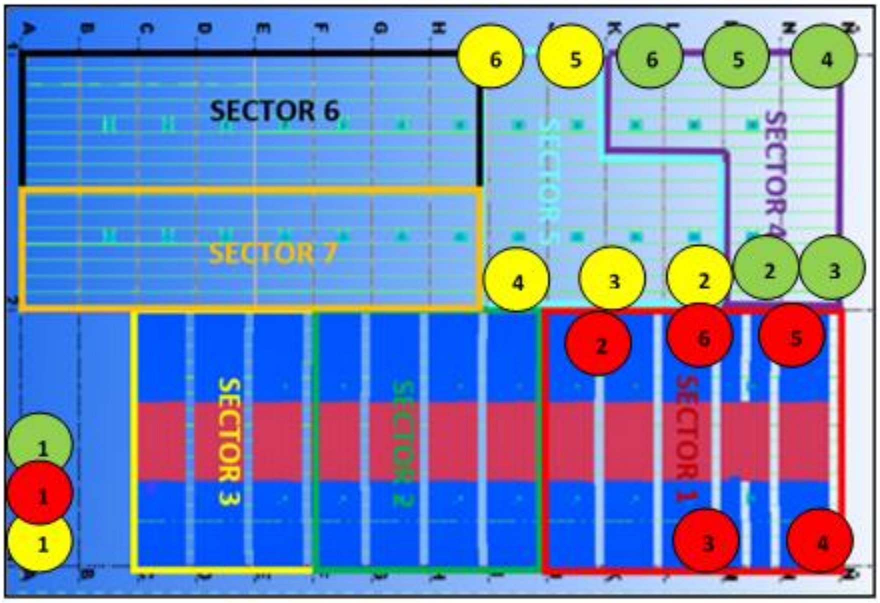

Figure 35. Floor plan with gateway marked

Uses during the experiment:

1) Planning:
   a. Control and follow-up (Validation of the programmed versus the executed in real time)
   b. Opportunities for improvement (Identify aspects not considered)

2) Production:
   c. Positioning (Verification of workers in the correct position performing the correct work)
   d. Routes and flows (Identify patterns of movements and times)

3) Security:
   e. Access control (Check the access of workers to authorized areas)
   f. Warning of dangerous areas (Warn the supervision of presence in dangerous areas)

Actual conditions on construction site are shown in Figure 36 and the registration process is shown in figure 37.

Figure 36. Onsite environment in Peru case study

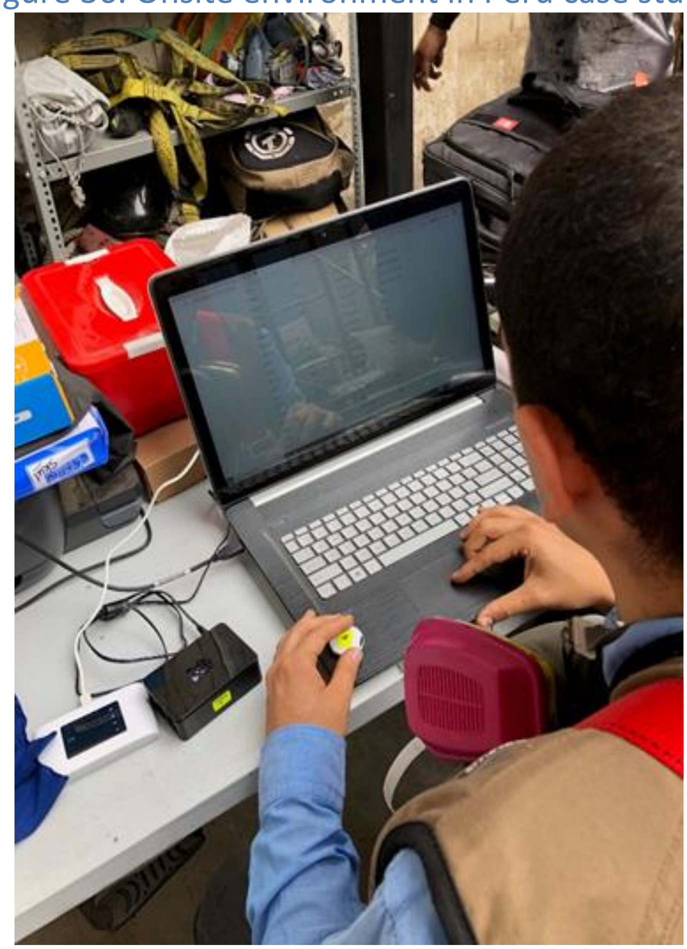

Figure 37 Beacons and gateways registration process onsite in Peru

Benefits and limitations of installation in Peru:

1. The biggest advantage was that iCONS provides information in real time, with a relatively low investment in hardware and managers are able to quantify productivity remotely with high precision.
2. The biggest limitations are that in non-industrialized contexts like Peru, this system needs somebody to check and re-calculate the outputs, because productivity needs to be quantified with the percentage of advance in order to manage the resources.

4.3.2 The Netherlands

Overview of the project and iCONS system set-up

The tracking was scheduled from week 46 to 50 (November 12 to December 11) in 2018 and 15 gateways were installed onsite. The construction site was a large building hub that consists of hotel, office, apartments and shops with a area of 22700 square meters at Noordgebouw , Utrecht (Figure 38). Our partner was hoping to track logistic flows between the supplier, the hub and the construction site.

Figure 38. The construction project after completion and its collaborators

The power supply strategy in this case was different than our implementation in Finland. The case study applied power banks for gateways due to the difficulties of having power onsite. Therefore, a battery replacement schedule was also planned along with Gateway placement schedule (Figure 39).

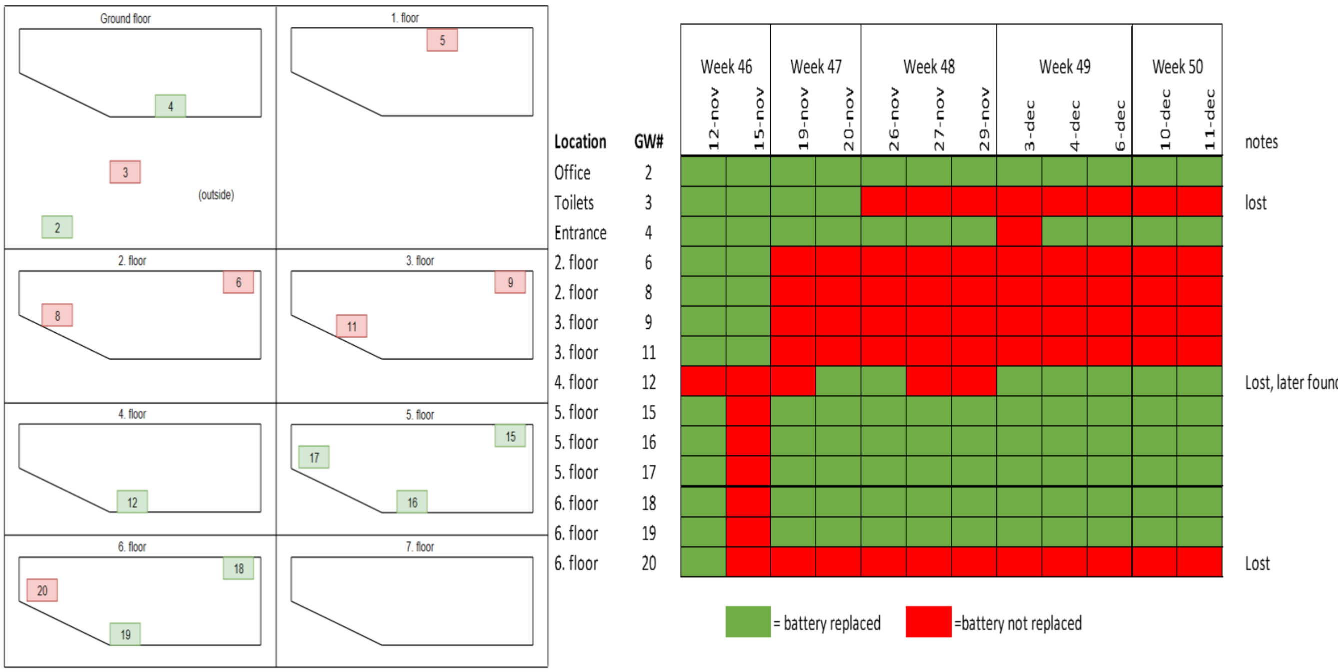

Figure 39 The floor plan with gateways marked (left) and battery replacement schedule (right)

Results/data analysis

The iCONS system returned the result for two workers' time spent information in different locations (figure 40). Additional analysis and comparison of Finland and Netherlands is underway as a continued research effort.

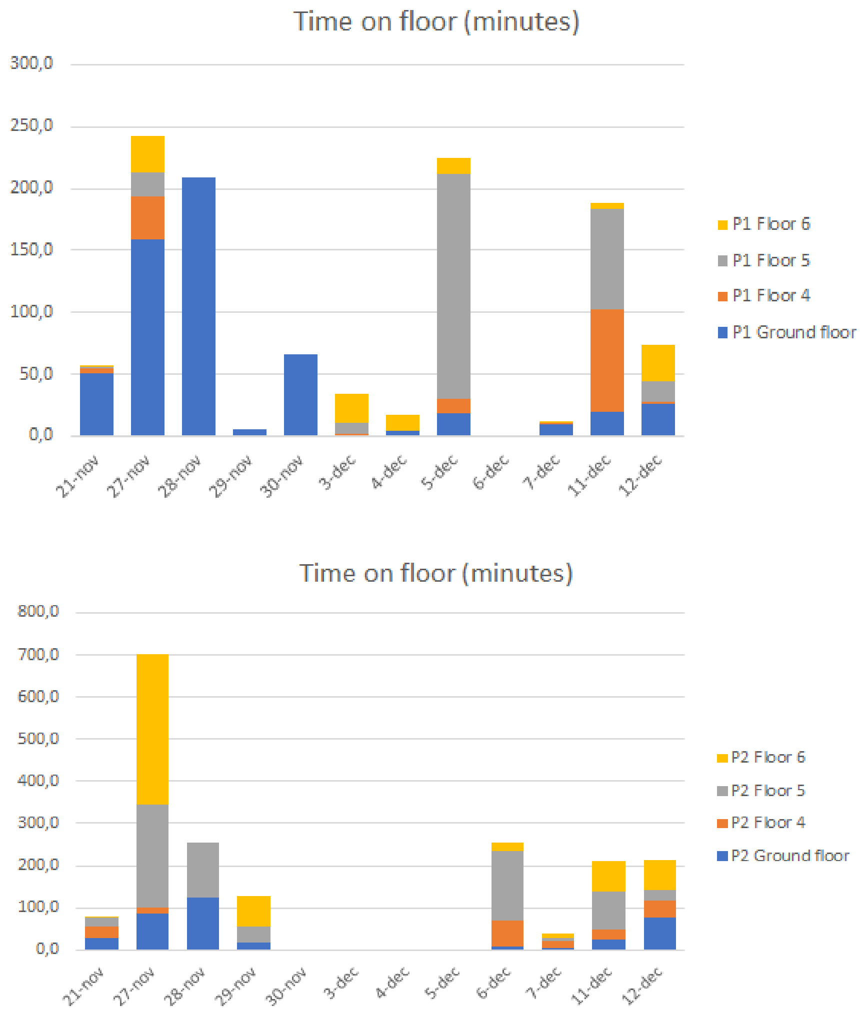

Figure 40. Personnel No.1 (up) and personnel No.2 (down) time spent information onsite

4.3.3 China

Overview of the project and iCONS system set-up

In partnership with Tianjin University, China, we tracked an MEP installation project in China. We selected an entire floor in an office building of around 1500 square meters (open space with length of 50 meters times width 30 meters) to test the iCONS tracking system. The jobsite is located in a city named ShiJiaZhuang that is 100 kilometers south to the capital Beijing. The tracking system monitored the work process of mechanical, electrical and plumbing jobs. We installed four gateways at each corner of the floor towards northeast, northwest, southeast and southwest. We set up one gateway in the middle near the entry of the floor. The initial setup process took about 7 hours and it took roughly 2 hours weekly for system maintenance. Figure 41 shows a floor plan of the jobsite with gateways installed.

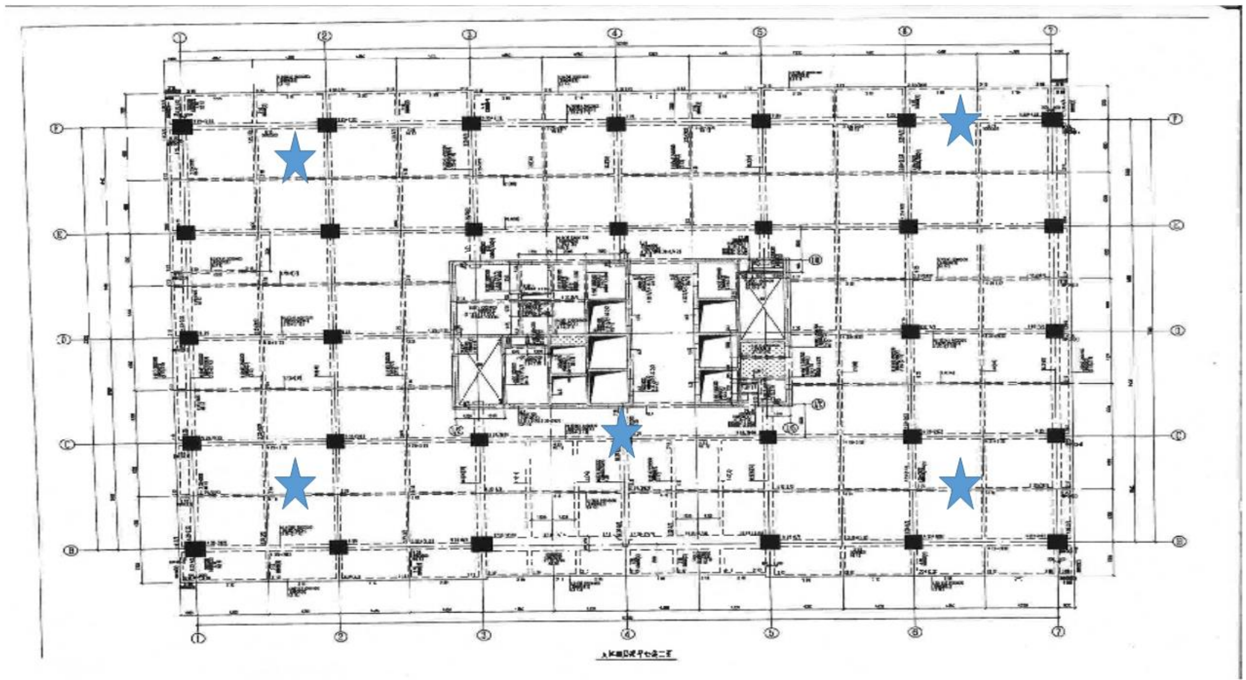

Figure 41 Real time tracking case study floor plan in China case

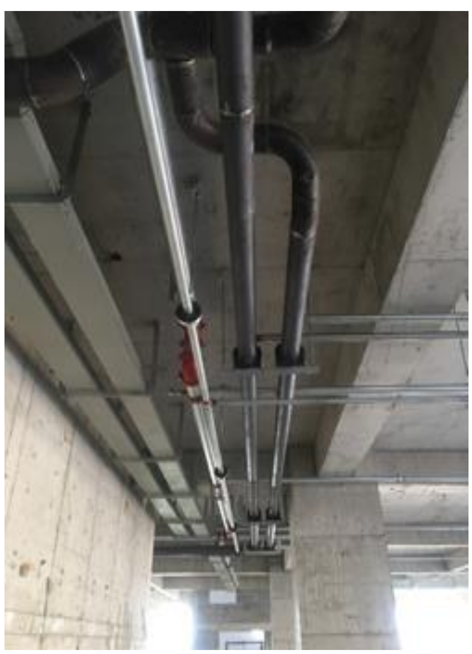

Figure 42. Onsite condition environment for iCONS system set-up

Results/data analysis

The visualization timeline of one worker we randomly picked was reduced indicating his/her daily movement (figure XX). The horizontal axis displays the timeline from 6am to 12pm and the vertical axis shows the different locations of gateways onsite. The rectangular squares in the figure indicates how long and where the worker spent his/her time at the place. The worker did not spent time in northeast area so the system automatically left out that location in the figure.

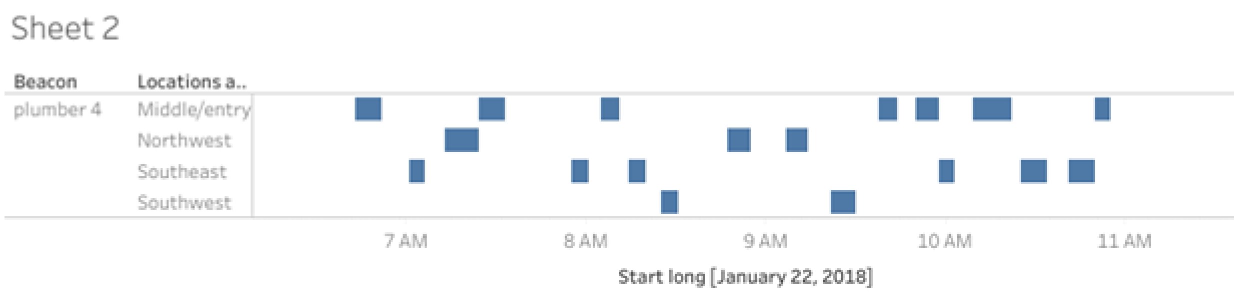

Figure 43 Movement visualization of tracking result for plumber 4 on January 22nd in Chinese case

From figure 43, it is clear to see the worker (plumber No.4) arrived at the entry of that floor at 6:43 am and he or she left the jobsite floor at 10:56am. It was a half day that the worker spent on the jobsite. The scattered movement patterns of this worker and others we tracked were as chaotic as those in Finland and did not match the planned work process. The same problems observed in Finland were also observed in China.

In China, the partners were very interested in safety control on site. For instance, if northwest area in this case was categorized as dangerous area with restricted access, site managers can check whether and when the workers have possibly been in the specific area. Because of the automated tracking process, the time and location information of the beacon carriers can be delivered to site managers or workers themselves in real time. We are continuing collaboration with Tianjin University to implement safety solutions on top of iCONS.

5. Results from construction company point of view (Written by Otto Alhava / Fira)

Fira is a general contractor and also develops a smart services platform aiming to transform from a Finnish construction company to an international technology company. Before iCONS project Fira had already started to digitalize the site, starting first from bringing broad band connections to the site office to enable BIM use. The first mobile applications for site use were already then in use on Fira's larger construction projects but using these solutions was problematic especially in the indoor construction phase. The use was and is still limited by poor connectivity inside construction projects, because the teleoperators build indoor coverage only after the building has been completed and the users have moved in. Digitalization of sites requires a temporary connectivity solution in the same way as a temporary power supply or temporary lighting is implemented.

From Fira's point of view the iCONS project happened at a very good time because there were already thoughts about digitalizing the construction site. Fira could not have advanced ambitious ideas about indoor positions and sensoring without iCONS project at the speed that was achieved in the project. The project sped up Fira's thought leadership's transition into action in three ways:

1) iCONS project brought together a group of unprejudiced companies from both construction and technology sectors to seek a solution to IoT-based indoor positioning problem
2) iCONS-project (in practice Aalto University) implemented a technical solution that helped show that digitalization and especially indoor poistioning is helpful to solve the productivity problem of construction
3) iCONS-project offered resources to implement pilots on Fira's projects and to help collect data which was able to detect root causes of poor productivity on site

It is important to note the leveraging impact of the iCONS -project on Fira's development as a company. Digitalization does not achieve a breakthrough with one application or one technological solution. Digitalization of the site and changing working patterns into digital age requires the bulding of a technology platform, open data platform, IoT solutions that work in construction site environment and cloud-based solutions which can be integrated based on the data platform. From Fira's point of view iCONS -project enabled the implementation of the first generation of technology platform and its architecture so that Fira did not need to use resources on development but they could focus on developing the production methods and production systems. In practice iCONS enabled the further development of SiteDrive and Open Data Platform and brought new actors to the ecosystem which helped Fira to develop IoT-solutions to construction sites. As a practical impact of this development to Fira, a lot of international attention has been gained and companies from United States, Germany, Nordic countries, the Netherlands and Asia are continuously visiting Fira. Because of Fira's technological advantage in market, they have been able to sign international collaboration agreements and also sell their solutions internationally.

6. Conclusion

iCONS project showed that indoor positioning systems and sensors on all assets (labor, material and equipment) is a critical part of digitalizing the site. They offer a way to measure waste and can concretely help in solving the productivity problem of construction waste. Although we set out to create new tools for site management, the key result of the project was a measurement and data collection framework which allows the effectiveness of site operations to be measured and compared to plans. The measure is somewhat objective and allows the comparison of different projects and even different industrial context.

The project was also successful for many of the participating companies. All construction companies were able to better understand the benefits of real-time data collection for construction process and what role IoT could play in site operations. Fira was able to significantly advance their development and use the project as leverage to get to international markets. Movenium (acquired by Visma during the project) created a commercial solution for positioning using some of the ideas developed in the project. Carina Solutions started offering services to construction industry. Trimble and Fira both were drivers to continue the work started in iCONS in a new Business Finland project DiCtion with substantial company development projects. It can be said that the research project changed the business of many participating organizations.

7. Future research directions

The work started in iCONS is continuing on many fronts after the project. Building 2030 consortium of 16 companies, including YIT, Skanska, Fira and Trimble from the iCONS project, is continuing to use the technology for measurement of waste. This includes more detailed data analysis of already collected data, new data collection with multiple devices and the use of results to try and solve the productivity problem of construction.

Based on iCONS, other Business Finland projects were started. We noticed already in the beginning of iCONS that we are not able to accurately know what has been completed just by looking at the location of assets. By combining the information that can be automatically gained from images, we could potentially come up with a more complete solution for situational awareness. Reality Capture project funded by Business Finland addresses the AI methods to automatically gain data from pictures.

The results of iCONS and RECAP generate a lot of data that is useful for measurement and analysis. However, different people in the construction process need different information to form a situation picture that is relevant to them. Just knowing where each asset is, is not a relevant situation picture. To solve the situation picture by using all available data streams and combining them together in a common ontology, is the goal of Digitalizing Construction Workflows project (DiCtion) which is funded by Business Finland and includes substantial development projects by participating companies. These three Business Finland projects can be seen as a continuum, first providing information about the possibilities of different data collection technologies and ultimately enabling situation awareness of the past, present and the future. After situational awareness has been achieved, the time for Artificial Intelligence is on us. The use of AI in construction is an exciting research avenue in the future.

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