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SITUATIONAL AWARENESS IN CONSTRUCTION PROJECTS USING TAKT PRODUCTION

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ABSTRACT

The construction industry is improving its processes targeting to increase productivity. Lean construction has been in use for decades, and now lean is expanding in the form of takt production. Takt production gives clear steps to apply lean in daily construction projects. Takt production transfers the improving flow from the manufacturing industry's conveyor belts to construction sites.

Digital situational awareness systems are good examples of new digital solutions in construction. They provide possibilities to construction stakeholders to better control and improve their processes by visualizing waste and helping find the root causes of problems to be fixed.

This paper aims to study how digital awareness systems support takt production in construction projects. This study is a qualitative case study based on a project implementing a digital situational awareness system and relies on project staff interviews and the data available on the project. The project team has successfully improved takt production with digital awareness systems for revealing and fixing waste. They have successfully improved the productivity of tasks. Digital situational awareness systems can play an important role in the continuous improvement of processes in the construction industry.

KEYWORDS

Productivity, lean construction, situational awareness, takt production, waste.

INTRODUCTION

Takt production has been proposed as a lean production planning and control method, resulting in several benefits, such as shorter cycle times and better transparency (Lehtovaara et al., 2021). Previous studies have investigated the link between takt production and prefabrication (Chauhan et al., 2018) and industrial logistics and takt production (Tetik et al. 2019). Still, few studies have discussed the digital tools required to support takt. Takt production requires problems to be solved within takt time (Frandson et al., 2015). Therefore, there is a need to see in close to real time how the actual construction is proceeding, how materials are being delivered, and get information of all

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the obstacles that prevent resources from working continuously according to takt production plan. New technologies related to digital situational awareness (SA) are being developed (Lappalainen et al., 2021) and becoming more real-time and they could play an important role in revealing waste as it occurs. There are technologies that pass-on the site status information digitally online without human interpretation. These systems are based on positioning sensors, cameras, drones, and 360-videos. There are so far no studies on how digitalized SA could support takt production and enable continuous learning, especially related to automatic waste detection and eliminating waste inside the takts during construction. This article aims to investigate the connection between digital SA and takt production in a single case where both were implemented in the same project and see how they can support each other. The study is exploratory research which is insightful to illuminate the understanding of a topic that is new or not studied earlier entirely (Saunders et al., 2009).

LITERATURE REVIEW

SITUATIONAL AWARENESS

SA concept was originally developed to improve safety in air traffic by giving better awareness of the situation to air traffic controllers and pilots (Harrald and Jefferson, 2007). Several industries like construction have adopted the idea of integrating the knowledge of repeated situation assessments to a coherent picture (Sarter and Woods, 1991). Situation assessments are complex and are limited by cognitive limitations of working memory and attentional capacity (Endsley, 1995). SA intends to help decision-making in a dynamic environment where data processing is limited by human cognition. Endsley's (1995) three-level SA model is the most widely used. It consists of three categories:

1. Observation of the current situation
2. Understanding of the current situation
3. Predictions of the future

Digitalized management increases in the Construction industry (CI) when digital platforms are used for production control and reporting purposes (Dong et al., 2006). Transparent and data-centric SA is based on applications and digital platforms. These digital solutions can be in the key role to solve the traditional problems related to CI projects (Aasland and Blankenburg, 2012). Although the SA concept was initially developed for other industries, there has been increasing interest in utilizing the concept in construction (Lappalainen et al., 2021).

Numerous papers have been written concerning SA and its sub-solutions for CI. The focus of these papers has been, on the utilization of work machines and equipment, occupational safety, and the role of BIM (Building information modeling) in SA (e.g., Lonsdale, 2004) and construction logistics management (e.g., Ghanem et al., 2018). Research has also focused on establishing a more holistic picture of the situation (O'Reilly et al., 2005) and integrating decentralized information in the CI (Kärkkäinen et al., 2019). Typical SA solutions evaluate the status of the environment, analyze the current status and create forecasts and alerts for decision making. So far, most attention has been given to analyzing the current status and most SA systems in construction are not yet good at projection (Lappalainen et al., 2021).

The new concept of Digital Twin Construction (DTC) proposed by Sacks et al. (2020) could fill these gaps in current solutions. Digital Twin Construction aims specifically at a closed loop system, where data about the actual process is collected during production, analyzed using AI methods and used to simulate and forecast future actions. Ultimately DTC aims to use information of production to help plan and design future projects. Sacks et al. (2020) indicate that while a lot of data is already being collected, positioning there are gaps in integration of multiple data sources. They list a lot of different data collection methods, of which tag identification systems, smart sensors and computer vision systems are used as part of the SA system described in this study. We explore the research gap indicated by Sacks et al. (2020) by manually integrating these data sources which can hopefully guide the future development of DTC systems.

TAKT PRODUCTION

Takt production has recently received a lot of attention in the lean construction community. The number of takt time related articles only in the five latest IGLC conferences is 29. Two alternative methods, Takt Planning and Takt Control (TPTC) and Takt time planning (TTP) have been proposed. TPTC approaches takt by defining functional areas and defining repeatable Standard Space Units (SSU) for each different function (such as an office). Then work packages are defined and quantities are calculated to determine the amount of work for each work package. Takt areas are combinations of SSUs (Binninger et al. 2017). In contrast, TTP (Frandson et al. 2013) approaches takt with a more bottom-up approach, emphasizing involving the trades who determine how they would like to work. Although collaboration can also be used as part of TPTC, TTP uses collaboratively defined work densities to determine appropriate takt areas. Both systems have a similar approaches to level production, including shifting scope, chancing manpower, or taking actions to decrease on-site work. In both systems capacity buffers are preferred, rather than time buffers typically favored by other location-based planning methods, such as the Location-Based Management system (Frandson et al., 2015).

However, although papers have documented several benefits, such as decreased project durations (Frandson et al. 2013), improved productivity (Heinonen & Seppänen 2016) and increased construction flow (Lehtovaara et al. 2021), very few cases have been reported with systematically collected empirical data. The only attempt to combine digital SA to takt production was reported by Alhava et al. (2019). The outcome of their study was that digital SA saved a takt production -project that could not follow takt production due to quality defects. The digital methods found a lot of waste in the project. Although the project was successful, and achieved a 30% cycle time reduction, the progress captured by digital systems was messy and revealed a lot of waste. In Alhava et al., (2019) study, the analysis was done after the fact. Our aim is to use digital SA to continuously analyze takt production to improve the process.

Continuous analysis of wasted effort in takt areas could play an important role in improving takt production. There are some previous studies in the literature where waste has been evaluated automatically based on indoor positioning. Zhao et al. (2019) proposed the concept of uninterrupted presence of workers in work locations which they claimed correlated with value-adding time. They later expanded the concept to task level (Zhao et al., 2021) and defined presence index as the share of uninterrupted presence during task duration. These metrics are used to identify opportunities for improvement in this research.

METHOD

This study is a qualitative exploratory case study with an inductive research approach. An exploratory study is insightful to brighten the understanding of an issue that is new or not studied earlier thoroughly (Saunders et al., 2009). Data collection methods are semi structured interviews, site observations and studying the project data produced by a SA-system. The research question driving this research was:

How can digital SA improve the use of takt production?

The studied project is a renovation project. The renovated real estate is an eighty-year-old former headquarters office building that consists of six and eight-story buildings. The A-building has already been renovated into a hotel, and the B-building renovation as office space is still active. All data in this study is from the B- building renovation project. The project is in a city center. The project delivery type was a modified version of a management contract. The management contractor has only management personnel, and all construction work has been procured from contractors. They all had a clause in their contracts that agreed to use the takt production system. The client and owner of the building is an investment fund.

The authors collected evidence by organizing interviews with the site superintendent and the productivity engineer (PE) who the digital SA provider employed. Interviews were supplemented by studying the digital SA data and making observations on site. The authors had access to all the data available in the system, including the PE's weekly reports. PE's information on the construction process was based on structured observations and participant observation. The structure of information PE collected was agreed upon with the customer before the project start and was secondary data for the authors.

In the semi-structured interview, the interviewee was given the discussion topics, and the interviewee answered openly. The topics were: general information about the project, takt production details, the SA system features and experiences, cooperation with the contractors, and improvement needs. The interviewer also asked some refining questions. The authors organized a site visit to supplement the interview findings.

The SA system was composed of indoor working area cameras, 360 videos, and the location information of resources using an indoor positioning system. There were altogether 11 indoor cameras whose location was determined by the contractors. The goal was to cover as large an area as possible with one camera and ensure that the cameras do not interfere with the work. One camera was directed to the inside yard to monitor logistics deliveries. At the beginning of the project, the management contractor took two 360 videos a week from each floor, but later one 360 video a week. The technology positioning the resources was based on low-energy Bluetooth (BLE). The location anchors were installed as a grid on each floor, and location beacons were installed on each worker's helmet. The location information was saved if the presence of the resource was at least two minutes. The presence was considered uninterrupted (Zhao et al., 2019) if the presence was at least ten minutes in a work location without breaks. The presumption is, that workers can only add value when their presence is uninterrupted at least 10 min on the planned area (Zhao et al. 2019). Around 60 Gb of data was collected each week. The data was managed in the data hub using a cloud service. SA system was supplemented with software for takt planning and software for logistics management. The project personnel used these three applications to understand takt planning, supply chain activities, and the locations of resources with comprehensive pictures of the status on site and documented activities for past weeks' work. This is the use of SA on category 2 in Endsley's (1995) three-level SA model. The indoor cameras covered two takt areas at the same time.

The project used a commercial solution for situational awareness. The system pseudonymized personal data by blurring images and not including the names of people in the tracking results. Researchers collected personal data for semi-structured interviews. Because the authors did not collect or handle sensitive personal data, an ethical review was not required.

RESULTS

SEMI STRUCTURED INTERVIEW AND THE SITE VISIT

The authors interviewed the site superintendent and the productivity engineer (PE). The author's site visit was organized at the later phase of the project. The site visit helped to understand the challenges with an old, renovation building in the city center. Logistics planning has an essential role in a successful project.

The case study project

The contractor's construction process was based on takt production. Each floor was divided into five takt production areas. There also were backlog areas where the takt production was not in use. In the first hotel renovation building, the contractor used a four-hour takt time per hotel room, but the takt time was selected to be eight hours (one working day) in the office building. There were masons, plumbers, drywall men, ventilation and pipe shafts masonry, plate wall work, soffits, plasterwork and painting, ventilation, pipelines, electricity, automation, and space surfaces resources in the indoor working phase teams. Then kitchens with glass walls, ceilings immediately after electricity, floor surfaces, listings, and door installations. The first resource plans were done based on the standard production planning database and then finetuned together with contractors. The production was planned using specific software for takt planning.

Experiences and improvement need

Camera information was used for general supervision. 360-videos were used for quality control. The 360 videos are helpful because it is possible to turn the view to specific locations in the room accurately. The superintendent could follow if the resources were in the right location and following the schedule.

The camera view and recordings were used during meetings to facilitate discussions of work done and the planning of future work. An indoor positioning system could show the actual location of resources. If the resources were not in the planned area, it was studied why the work could not be done according to the plan. The PE used camera and presence information and site visits to investigate waste. PE improved productivity by giving feedback twice a week in site meetings with the superintendent and contractors. PE also wrote weekly reports of the observed wastes and suggestions on how to fix them.

The system helped improve supply chain reliability and reduced schedule risks. The PE's weekly reports highlighted the deviations in the logistics. At the beginning of the project, the number of logistical variations that stopped the work was fifteen each week. PE could follow the logistic deliveries using the specific application. PE reported the logistics deviations and started the discussions with the contractor to improve the deliveries matching better to the actual need on site. The use of the system reduced the number of fatal logistical deviations to five deviations per week.

Uninterrupted presence in work locations helped to identify wasted effort and with PE investigation, several wastes were identified and fixed. For example, on weeks 40…42, PE reported a constantly low presence index of floor rebar contractors and several short visits to other floors, and several work interruptions. PE reported on week 41 that the materials should be moved to the work area and reschedule the use of resources so that work is uninterrupted by increasing assistant work resources. As a result of the feedback, on week 43, PE reported that the active presence had risen from 20 % to 70 %.

The site superintendent’s feedback on the SA system was positive, and he was keen to use the system in the following projects. He also pointed out that the cameras do not replace human supervision on site. Construction is teamwork, and human contact is necessary. The interviewees stated that the plumbing resources had more difficulties following the takt plan than the electricians. The location information (figure 3) confirmed that the electricians could better follow the takt plan.

However, several improvement areas were also noticed. In this case, the agreement between management contractor and their contractors did not include clauses about the utilization of resource positioning. This led to difficult discussions when workers needed to be convinced to carry a positioning beacon. However, the project team convinced all the important contractors to participate in positioning. Going forward, there should be a description and requirement in project agreements explicitly describing the SA system and the use of people tracking on the project. The preliminary information and training of the contractors' workers are essential.

The technology of resource positioning was prone to the fact that sometimes the positioning anchors were moved from their location, e.g., before painting. Sometimes there were not enough electricity plugs, which caused the electricity source of anchors’ to be used for construction equipment. Sometimes the workers had just forgotten to take the positioning beacon with them. The site superintendent suggested that the system provider implement the positioning beacon in the same sticker as the information of passed security training, which the workers must use.

DATA OF THE CASE PROJECT

PE documented the observations of the location of resources, duration of tasks, logistical deviations, and other waste observations weekly. The SA software stores the data in the data hub in cloud. Figures 1 & 2 are screenshots of the SA-application. In figure 1, there is a view of one electrician's presence in second floor takt areas 1…5 on 15 minutes levels. It can be seen that the electrician was moving between several takt areas and spent most of the time on areas 4 and 1 on the second floor. According to the takt plan, the electricians should work on first floor area 2. In figure 2, there are the actual locations marked as red dots concerning area 1. It is then possible to drill in and identify on the floor plan how

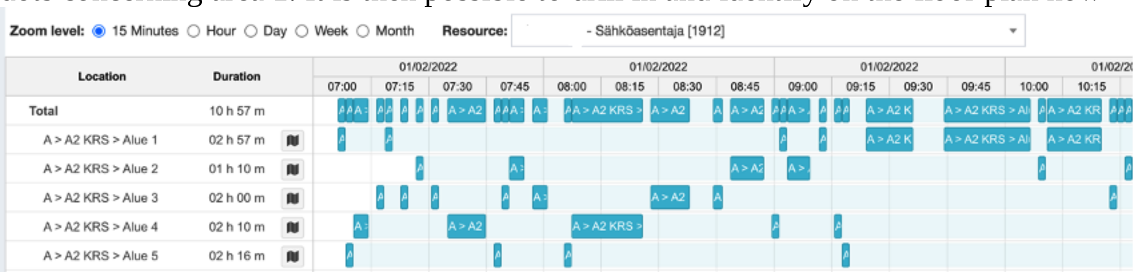

Figure 1. The figure shows an Electrician’s presence on the second floor takt areas during a working day.

much time was spent on planned areas and how much time on storage areas and other areas that does not add value. Analysis of waste on task level made it possible to fix the problems rapidly, which was a requirement due to the short takt time of 8 hours.

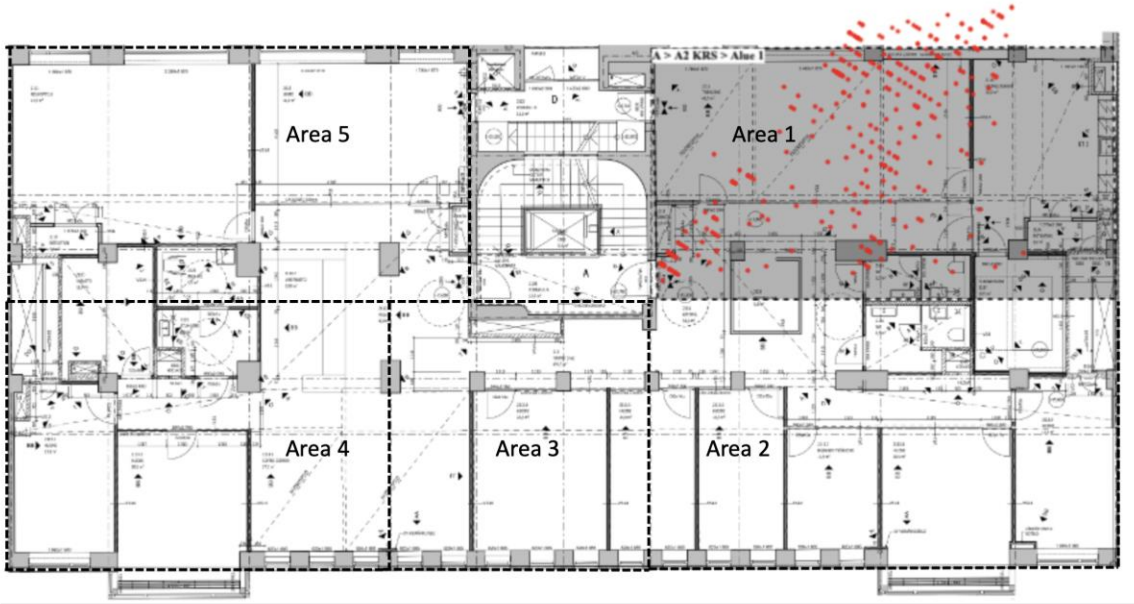

Figure 2. The figure shows an electrician's presence indicated as red dots on the second floor takt area 1 (Alue1) during a working day.

Figure 3 shows an overview of presence during several weeks. The time flows vertically (week numbers) and takt areas are shown on the horizontal axis. This picture gives an instant view of how well the resources follow the takt production plan (thicker cells). The plumbing resource (upper table) has high deviations in task locations, which is a sign of disturbances. The percentage in each cell should be 20% if one week's plan includes five days. Electricians were able to follow the takt plan with fewer deviations. The presence

Week	A > A1 KRS > Alue 1	A > A2 KRS > Alue 1	A > A2 KRS > Alue 2	A > A2 KRS > Alue 3	A > A2 KRS > Alue 4	A > A2 KRS > Alue 5	A > A2 KRS > Rappu	A > A3 KRS > Alue 1	A > A3 KRS > Alue 2	A > A3 KRS > Alue 3	A > A3 KRS > Alue 4	A > A3 KRS > Alue 5	A > A3 KRS > Rappu	A > A4 KRS > Alue 1	A > A4 KRS > Alue 2	A > A4 KRS > Alue 3	A > A4 KRS > Alue 4	A > A4 KRS > Alue 5	A > A4 KRS > Rappu	A > A5 KRS > Alue 1	A > A5 KRS > Alue 2	A > A5 KRS > Alue 3	A > A5 KRS > Alue 4	A > A5 KRS > Alue 5	A > A5 KRS > Rappu	A > A6 KRS > Alue 1	A > A6 KRS > Alue 2	A > A6 KRS > Alue 3	A > A6 KRS > Alue 4	A > A6 KRS > Alue 5	A > A6 KRS > Rappu	A > A7 KRS > Alue 1	A > A7 KRS > Alue 2	A > A7 KRS > Alue 3	A > A7 KRS > Alue 4	A > A7 KRS > Alue 5	A > A7 KRS > Rappu	A > A8 KRS > Alue 1	A > A8 KRS > Alue 2	A > A8 KRS > Alue 3	A > A8 KRS > Alue 4	A > A8 KRS > Alue 5	Total huors
46	2 %	4 %	0 %	1 %	1 %	0 %	0 %	0 %	1 %	1 %	1 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	87 %	0 %	0 %	0 %	0 %	04:33
47	1 %	1 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	1 %	1 %	1 %	0 %	93 %	0 %	0 %	0 %	0 %	19:16
48	5 %	3 %	0 %	2 %	2 %	1 %	0 %	1 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	1 %	0 %	4 %	0 %	1 %	0 %	24 %	11 %	17 %	4 %	9 %	0 %	13 %	0 %	0 %	0 %	0 %	13:02
49	4 %	3 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	2 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	15 %	0 %	0 %	0 %	1 %	0 %	66 %	1 %	0 %	0 %	3 %	0 %	2 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	09:06
50	7 %	1 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	1 %	0 %	7 %	13 %	14 %	11 %	15 %	0 %	2 %	2 %	6 %	2 %	3 %	0 %	0 %	0 %	1 %	0 %	1 %	0 %	9 %	0 %	0 %	0 %	0 %	73:25
51	4 %	2 %	0 %	3 %	0 %	10 %	0 %	2 %	2 %	12 %	0 %	2 %	0 %	8 %	3 %	12 %	7 %	5 %	0 %	0 %	0 %	2 %	0 %	1 %	0 %	4 %	2 %	3 %	1 %	2 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	4 %	3 %	0 %	1 %	3 %	61:01
52	6 %	5 %	0 %	3 %	0 %	0 %	0 %	0 %	1 %	7 %	0 %	0 %	0 %	7 %	6 %	11 %	6 %	2 %	0 %	3 %	5 %	2 %	2 %	1 %	0 %	1 %	1 %	1 %	2 %	3 %	0 %	3 %	6 %	2 %	4 %	6 %	0 %	0 %	0 %	0 %	0 %	1 %	82:12
1	1 %	1 %	1 %	6 %	0 %	1 %	0 %	11 %	11 %	34 %	13 %	9 %	0 %	1 %	3 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	1 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	60:08
2	4 %	26 %	0 %	0 %	0 %	1 %	0 %	2 %	6 %	24 %	15 %	18 %	0 %	1 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	2 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	05:27
3	23 %	53 %	0 %	1 %	2 %	2 %	0 %	3 %	0 %	3 %	1 %	1 %	0 %	1 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	3 %	0 %	0 %	0 %	0 %	0 %	2 %	74:27
4	30 %	10 %	7 %	12 %	8 %	13 %	1 %	0 %	1 %	0 %	1 %	1 %	0 %	0 %	1 %	1 %	1 %	1 %	0 %	0 %	2 %	0 %	1 %	1 %	0 %	0 %	0 %	0 %	0 %	2 %	0 %	0 %	1 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	76:02
5	16 %	3 %	0 %	0 %	0 %	2 %	1 %	1 %	1 %	3 %	1 %	4 %	2 %	2 %	1 %	1 %	2 %	3 %	1 %	5 %	3 %	1 %	2 %	4 %	0 %	1 %	0 %	1 %	2 %	1 %	2 %	6 %	5 %	4 %	15 %	3 %	0 %	0 %	0 %	0 %	0 %	0 %	61:09
6	6 %	2 %	0 %	0 %	1 %	3 %	1 %	0 %	0 %	1 %	3 %	16 %	2 %	3 %	2 %	0 %	1 %	1 %	1 %	0 %	0 %	2 %	2 %	4 %	1 %	20 %	3 %	5 %	11 %	3 %	1 %	0 %	0 %	1 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	29:26

Week	A > A1 KRS > Alue 1	A > A2 KRS > Alue 1	A > A2 KRS > Alue 2	A > A2 KRS > Alue 3	A > A2 KRS > Alue 4	A > A2 KRS > Alue 5	A > A2 KRS > Rappu	A > A3 KRS > Alue 1	A > A3 KRS > Alue 2	A > A3 KRS > Alue 3	A > A3 KRS > Alue 4	A > A3 KRS > Alue 5	A > A3 KRS > Rappu	A > A4 KRS > Alue 1	A > A4 KRS > Alue 2	A > A4 KRS > Alue 3	A > A4 KRS > Alue 4	A > A4 KRS > Alue 5	A > A4 KRS > Rappu	A > A5 KRS > Alue 1	A > A5 KRS > Alue 2	A > A5 KRS > Alue 3	A > A5 KRS > Alue 4	A > A5 KRS > Alue 5	A > A5 KRS > Rappu	A > A6 KRS > Alue 1	A > A6 KRS > Alue 2	A > A6 KRS > Alue 3	A > A6 KRS > Alue 4	A > A6 KRS > Alue 5	A > A6 KRS > Rappu	A > A7 KRS > Alue 1	A > A7 KRS > Alue 2	A > A7 KRS > Alue 3	A > A7 KRS > Alue 4	A > A7 KRS > Alue 5	A > A7 KRS > Rappu	A > A8 KRS > Alue 1	A > A8 KRS > Alue 2	A > A8 KRS > Alue 3	A > A8 KRS > Alue 4	A > A8 KRS > Alue 5	Total huors
1	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	3 %	0 %	2 %	0 %	2 %	0 %	18 %	17 %	18 %	15 %	21 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	27:07
2	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	32 %	11 %	12 %	6 %	1 %	0 %	2 %	2 %	2 %	1 %	3 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	2 %	1 %	1 %	19 %	2 %	07:10
3	0 %	0 %	0 %	0 %	0 %	1 %	0 %	19 %	7 %	9 %	9 %	26 %	0 %	1 %	0 %	3 %	2 %	8 %	0 %	1 %	1 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	2 %	2 %	6 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	69:36
4	1 %	20 %	4 %	8 %	13 %	14 %	1 %	7 %	3 %	6 %	5 %	11 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	1 %	2 %	1 %	1 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	66:05
5	1 %	35 %	8 %	10 %	9 %	19 %	1 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	3 %	0 %	0 %	1 %	0 %	7 %	1 %	0 %	0 %	0 %	0 %	0 %	62:53
6	1 %	33 %	1 %	1 %	2 %	3 %	0 %	0 %	0 %	0 %	1 %	3 %	0 %	0 %	0 %	0 %	0 %	3 %	0 %	0 %	0 %	0 %	0 %	0 %	1 %	1 %	0 %	0 %	0 %	8 %	8 %	20 %	0 %	1 %	0 %	13 %	1 %	0 %	0 %	0 %	0 %	0 %	43:49

Figure 3. Weekly summary of the plumbing (upper table) and electrical (lower table) resources' uninterrupted presence. Thicker cell borders indicate the planned tasks, and green cells are the actual locations that follow the plan. Red cells are locations outside planned areas. Rows are a weekly (five working days) summary of all resources' activities (13 plumbers and 9 electricians had the positioning beacon) in the takt areas.

in the planned takt areas is relatively small, indicating that there is still much room for improvement. If waste can be eliminated and presence indices increased, the risk of delays lowers and the takt times could be planned shorter in the future.

The SA system may also include condition sensors with max and min alerts which can be used to evaluate whether external conditions are available to start work. PE's task is to follow all this digital information and report the site management regularly deviations.

DISCUSSION

A SA system has three levels (Endsley, 1995). The study results show that the digital SA system provides level 1 and 2 information that improves the use of takt production. The digital SA system provides observations of the takt production status. Different camera and video information and outputs like individual workers' location at 15 minutes intervals (figure 1) are examples of the observations. The schedule where the actual workers' presence is combined with the planned takt production tasks (figure 3) helps to understand the outcomes of waste. The current system still needs PE to point out the critical observations and support the superintendent in understanding the meaning of observations. The observations show the waste like low presence index, which root cause can be deviations on material delivery or in work arrangements on site. Level 3 predictions of the future are still on PE's and superintendent's responsibility. In the future, AI may detect waste and its root causes and predict the delays and other challenges based on on-site observations.

The digital SA provider's PE gave the site manager and contractors weekly reports. In practice, PE finds waste, which was made visual by using site cameras, 360-videos, and resources location tracking. Some of the findings were valuable. The fatal deviation of material deliveries was managed to drop from 15 to 5 per week. The positioning system of resources gave the accurate location of resources and the time of presence. It was possible to calculate the real presences percent on the takt area. The project team was able to improve the presence index from twenty to seventy percent in some cases.

The system had significant benefits, and it helped the site superintendent detect waste and then find the root cause and fix it. The system produces reliably the actual schedule (figure 3) based on the real resource actions on site. There are things to improve as well. The use of a digital SA system should be mentioned in the project agreement. The project staff should be informed and explain why the digital SA system has been implemented and the benefits for each stakeholder group. The positioning grid's installation had challenges when the tags were removed during painting. The location sensor should be attached to each worker's helmet at the beginning of the project and not allow workers to keep the sensors in pockets, where they quickly forget.

It is good to point out that the waste found was concerning individual processes in takt. The improvements did not shorten the planned whole construction duration because it is hard to change the whole takt train if some operation can be improved. However, decreasing waste is directly beneficial to the participating contractors, who can then consistently hit their takt times and it also reduces the schedule risk of the main contractor. The largest opportunities arise if the use of digital SA systems is continuous and used in all projects. The data should be collected more systematically to evaluate how much buffer there is in task durations and capture lessons learned to future takt projects. In this project, tasks had a different variance in their durations. When the variance lowers due to continuous development, it gives the site management possibilities to decrease the takt times and thus the total duration in the next project. All this data of the actual resource positions during several projects helps the resource planning in the following projects. The actual information of resource locations in projects can later be used for artificial intelligence (AI) solutions to predict project delivery success versus planned turnover and project costs. AI can later detect waste and suggest how to fix it.

This study was based on the data of one construction project. Therefore, there are limitations on how to apply the results. The variance of the observations was also high. This study gives good reasons to make new studies using digital SA systems and takt production together. The combination could decrease the risk of schedule overruns, uncovers production problems, and makes it possible in the long run to continuously improve takt production and achieve shorter takt times which ultimately can shorten construction durations without sacrificing quality and cost.

CONCLUSIONS

According to Sauders et al. (2009), the exploratory case study method can be used if an issue is new or not studied earlier thoroughly. The SA technology is new, and the experience of using it to improve takt production is also new. The best advantage the digital SA provides to takt production projects is that it gives online information on how the project proceeds. The data is reliable because it has been produced automatically without human interpretation. Project staff can react to the information found and fix the issues before turning them into loss, delays, or other waste. Many other systems (Alhava et al., 2019) give the information afterward, and the information is based on the workers' interpretation.

In this case, it was easy to recognize the recurring structures of the SA system. Status of the environment and observations were simple to authenticate from site cameras, 360 videos, and location data of resources. It helps to understand the current situation. Since the observations were real-time, the waste could be detected and could be easily improved by analyzing the process. This helped in the production of future takt areas. The location reports of resources showed the status of takt production and were a basis for the future status prognosis. Real time views produced by SA system and PE's reports were the basis for decision-making. SA system and PE make the waste visual, and site management makes the decisions based on these facts.

The goal in the case project was to use digital SA to continuously analyze takt production to improve the process. The digital SA system made the waste visual. PE's report highlighted the findings to the site manager responsible for finding the root cause and fixing the issues. As a result of this study, the SA system gives tools to construction sites to analyze production on time and react to found issues. SA systems produced valuable data on the construction project. It would be feasible to collect data continuously on the takt production project and individual resources performance. This data can be a basis for continuous improvement on construction sites. The data was manually analyzed in this study. When the analysis becomes automatic through AI methods, we are one step closer to achieving the vision of Digital Twin Construction (Sacks 2020).

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