DIGITAL TOOLS TO INCREASE CONSTRUCTION SITE SAFETY

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The purpose is to investigate the use of digital tools to mitigate risks and increase worker safety at construction sites. Construction is one of the most dangerous industries to work in with relatively high numbers of injuries and fatalities. At the same time there is an ongoing trend of digitalization of construction, and digital technologies, including, i.e., electronic tools, systems, devices, embedded sensors, that generate, store, or process data, are introduced to the construction sites, also for safety applications. Based on five case studies, this study investigates the use of digital technologies for improving site safety. All cases are a part of a larger project where digital technologies, including sensors, edge cameras and computers, object recognition, AI, cloud computing, etc., are tested in a "real environment", on-going construction projects. The analysis focuses on three areas: the technical feasibility, user acceptance, and the possibility to scale-up and commercialise the digital technologies. The results show that the construction context puts extra demand on development when it comes to technical feasibility, whereas the user acceptance is generally good. The main challenge is, however, to show commercial benefits and scale-up the technology for broader implementation in the industry.

Keywords: AI; communication; H&S; digital twin; innovation; sustainability

INTRODUCTION

Construction is one of the most dangerous industries with relatively high numbers of injuries and fatalities. To take Sweden, with high demands on safety, as an example, there was a yearly average of 11 injuries per 1000 employees reported between 2014-2019 (Arbetsmiljöverket, 2021). Hence, construction was the industry in Sweden with the second highest number of injuries reported, right after manufacturing, while at the same time having the highest number of reported fatal accidents per year. Looking more closely at what causes the accidents, Samuelsson (2019) found the most frequent causes to be: damage from tools (18 %), body movements and physical body load resulting in stress injuries (17 %), falls at the same level (stumbling) (13 %), fall from height (11 %), and vehicle and machine related injuries (12 %). Although vehicle and machine related injuries are reported as only 12 % of the total injuries, 206 out of 434 (47 %) deaths on construction sites in Sweden between 2010 and 2019 were due to lost control of vehicles and machines, being by far the main reason of deaths on construction sites (Arbetsmiljöverket, 2019).

At construction sites, different groups of professionals, including skilled workers and machine operators, work simultaneously and safe interaction between heavy vehicle

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This paper was presented as a working paper at the ARCOM 2022 Conference, Glasgow Caledonian University, Glasgow, UK, 5-7 September 2022. Please contact the authors before citing.

operators, crane operators and other workers is crucial for safer construction sites (Sanni-Anibire *et al.,* 2020). Wearing the correct safety equipment and gear, planning for, and taking the correct safety measures, and establishing good communication systems between different groups of workers is essential, especially in construction sites with limited space and high time pressure.

At the same time there is an ongoing digitalization of construction (Qi *et al.,* 2021), and digital technologies, including, i.e., electronic tools, systems, devices, embedded sensors, etc., that generate, store, or process data, are introduced to the construction sites (Chauhan *et al.,* 2021). Recent research report on a growing trend to adopt digital technologies among construction companies (Chen *et al.,* 2021), exemplified by, e.g., Building Information Modelling (BIM), track and trace technologies (e.g., RFID), immersive media technologies (e.g., virtual reality and augmented reality), and embedded sensors of various types (Qi *et al.,* 2021, Chen *et al.,* 2021).

Construction firms employ digital technologies to improve communication between project stakeholders and for construction automation, data acquisition, visualisation, and analytics (Chen *et al.,* 2021). The adoption of digital technologies has also been reported to improve the construction process as such, not only including design, production, logistics and procurement of materials and services (Gholami *et al.,* 2019), but also site safety (Park *et al.,* 2017). However, many of the studies are based on tests in labs or controlled site settings, rather than site implementation in "real", on-going construction projects (Rao, *et al.,* 2022).

Hence, the purpose is to investigate the use of digital tools to mitigate risks and increase worker safety at sites in on-going construction projects. The empirical data is collected from five case studies employing different types of digital technologies. The case data is analysed from three perspectives and discussed from a general standpoint.

Safety Technologies in Construction

Digital technologies for safety applications

There are currently a multitude of digital tools that are entering construction and construction sites (Rao, et a., 2022), including sensor technology, IoT applications and real-time monitoring of site activities. In addition, digital technologies offer possibilities to improve site safety by, for example, providing real-time alerts and warnings to workers on potential hazards and incidents, as well as real-time, and sometimes automated, communication between workers, machines, and managers (Zhao, et.al., 2021). In this study three different sets of digital technologies have been employed: AI and vision systems, Smart wearables and digital twins, and Bluetooth technologies for communication.

AI-powered vision technology systems employ cameras for object detection, positioning and recognition. The cameras can be of different types, e.g., IR or RGB. IR sensing technologies detect the reflecting light in the infrared region of the electromagnetic spectrum, whereas RGB cameras capture high-resolutions images that can be processed using photogrammetric techniques (Rao *et al.,* 2022). The cameras are typically mounted stationary, on equipment (cranes, heavy machines, etc.), or as wearables (cloths, helmet, backpack, etc.). Images from both IR and RGB cameras can be analysed and processed using machine learning-based AI technology for object detection, object classification, proximity alerts, etc.

Smart wearables include sensors that are worn and attached to a body part, cloths, or worker equipment (e.g., helmets). The smart wearables can include sensing technologies like positioning systems (GPS, short-range (e.g., BLE), etc.) and inertial measurement units (IMUs) such as accelerometer, gyroscope, etc. When combining smart wearables with digital twins it is possible to monitor the construction site environment, workers, and hazardous situations in real-time (Rao *et al.,* 2022). A digital twin is a digital representation of a physical reality (a building, a construction site, etc.) where the digital representation is feed with data from the physical reality and provides information to the physical reality to act upon (e.g., safety alerts, better informed decision-making, digital safety barriers, etc.). The data/information exchange should preferably be in real time, but due to technical and/or managerial constraints the exchange can also be batched/periodical.

There are various ways to communicate on construction sites including verbal communication, hand signals, two-way radio communication and wearable Bluetooth communication technologies. Traditional channels of communication represent several problems including noise and congestion limiting verbal communication and one hand being occupied with holding the radio (Mansoor, *et al.,* 2020). Although Bluetooth headsets solved the problem associated with engaging one hand to hold the communication device (Tsai, *et al.,* 2009), the headsets still suffer from other problems including noisy areas and range of communication. The new BLE technology (Bluetooth Low-Energy) is more energy efficient and has a range of up to 30 meters (Rao *et al.,* 2022).

Implementing digital safety technologies

There are numerous drivers for implementing digital technologies (Sepasgozar *et al.,* 2016), but here we focus on technologies that facilitates site safety. The technology implementation as such is often an iterative process (Jacobsson and Linderoth, 2010), including pilot testing of the technology, and the decision on full-scale implementation is typically shaped by the lessons learnt from these pilot tests. Pilot tests are experiments using the digital technology in its real environment and can be evaluated based on the technical feasibility, the user acceptance, and the possibilities to scale-up and commercialise the technology.

Technical feasibility is the process of validating a technology in its real environment, including the technology assumptions, the technical architecture and the actual design and operation. Evaluating the technical feasibility involves testing a working model of a product, or the product itself. It is, however, not necessary that the test is carried out with what will be the final version of the product. The purpose of the technical feasibility test is to demonstrate that the product is functional in its intended environment. The examination results in the clarification whether the technical presentation of the problem is viable in general and, in a further step, whether it is viable for the company (Bause *et al.,* 2014). Technical feasibility can include proof of concept (POC), proof of value (POV), and other types of technology analyses.

Technology acceptance of users can be influenced by many factors; however, Davis (1989) reduced these factors to only two: perceived usefulness and perceived ease of use. In a more recent model, Venkatesh *et al.,* (2003) includes four constructs: performance expectancy, effort expectancy, social influence and facilitating conditions. While performance expectancy and effort expectancy are alike perceived usefulness and perceived ease of use, social influence and facilitating conditions are new constructs. At a construction site, social influence can include pressure from other workers, site management and clients while facilitating conditions can be whether the company (i) supports required infrastructure for the technology and (ii) offers training, education, and support for the technology (Sezer and Bröchner, 2019).

Commercialisation is the process of bringing new products, or services, to market. Often a commercialisation process starts with a stepwise scale-up after a successful technical feasibility test. The stepwise scale-up typically includes enhancements to the product and testing on a larger scale (e.g., in more sites, projects, etc.). If the scale-up provides positive results, the next step is commercialisation on a broader scale. The broader act of commercialization entails production, distribution, marketing, sales, customer support, and other key functions critical to achieving the commercial success of the new product. The scale-up process generates knowledge to transfer ideas into successful commercial implementation (Harmsen, 2019).

METHOD

This study is part of a large Swedish research project focusing on the digitalization of construction sites. The project includes several testbed projects involving 30 pilot tests of different digital technologies. The pilot tests focus on the actual testing of technologies in a specific context prior to full scale implementation. Here, five pilot tests focusing on construction site safety are analysed, where the five pilot tests are regarded cases in a multi-case setting. The study is of an explorative nature, testing different means to mitigate risks and increase worker safety on site, thereby paving the way for ongoing development of digital safety tools and further research on their applicability and effectiveness for reducing risks, injuries, and fatal accidents at construction sites. Primary data from the five cases have been collected using site observations, semi-structured interviews, surveys, participation in weekly pulse meetings for each pilot test and regular discussions with project managers, consultants, site personnel, etc. Secondary data has been collected from project descriptions, project reports, project presentations, and performance indicators collected by project participants. The collected data has been analysed from the perspectives of technical feasibility, user acceptance, and possibilities to scale-up and commercialise the products and/or systems that have been tested.

FINDINGS

The five cases are described in the following, including the setup of each respective pilot tests and the identified findings, which are summarized in Table 1.

Safety equipment cameras

Having the proper safety equipment when entering through the gates of a construction site is crucial both for personal safety and for visual detection by co-workers in heavy machines, cranes, etc. This case aimed at analysing the compliance to safety policies by using an IP RGB camera at the gate, with deep learning AI, computer vision and object detection (see *Figure 1*). The algorithms of the cloud-based AI were trained to detect the use of HVC, helmet, helmet chinstrap, and protection glasses. A dashboard was placed at the gate for real-time visual feedback on the safety equipment compliance to the worker and compliance data was analysed on an aggregate level to be used as basis for the continual safety work on site.

A large set of images was collected and manually annotated for training the AI, and the technical feasibility was generally good. HVC and helmets where easily detected, but it was difficult to detect if the chinstrap was correctly used, e.g., on men with a beard. Similarly, it was possible to detect glasses, but hard to determine if they were protective or ordinary glasses. These issues can be resolved as the AI gets more images to practice on, the more the system is used. Detection can also be improved by using an additional camera from a different angle. The user acceptance was generally good. Initially there were some concerns for personal integrity, but since there is no personal identification and since no images are stored, these concerns where resolved. On a project level the aggregate compliance data was appreciated and was an important tool for initiating site safety improvement work.

Notably was that during the trial period helmets were used by 96 % at the workers passing through the gate, while the compliance for the other safety equipment was much lower (between 58 and 73 %) even though the use of full safety equipment is mandatory at the site. The companies participating in the pilot test where the main contractor, a company providing rental equipment, a digital tech consultant, and an AI and cloud computing provider. After the test period, the company providing rental equipment decided to continue the development of the system, which was supported by the main contractor. The digital tech consultant was engaged to enhance the deep learning AI parts of the system. An upgraded version of system is now tested in both demonstration facilities and on construction sites, and the rental equipment company plan to commercialise the system as part of their product portfolio for site safety.

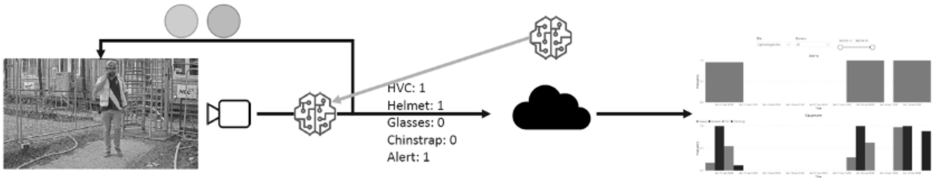

Figure 1: The setup of the safety equipment camera case

Crane IP cameras

Working close to and under cranes is one of the most dangerous work areas when it comes to severe and fatal accidents. This case aimed at preventing personnel from being under suspended load from a tower crane using deep learning AI, computer vision and object detection. The setup is visualized in *Figure 2*, where two IP cameras are mounted on the crane jib and an IoT edge computer and a dashboard screen is installed in the crane cabin. These are connected to a local network and a 4G router, so that statistics and selected images can be uploaded to the cloud for model training and development. The objects on ground (i.e., workers) are observed, detected and tracked in real-time. Notifications and alerts are automatically displayed to the crane operator if workers are within a defined safety zone/restricted area beneath the crane jig.

There were several challenges when it comes to the technical feasibility: object detection and tracking from a birds-eye perspective and developing the deep learning algorithms for this case, establishing connectivity at site and reliable hardware for both edge and cloud computing capabilities and performance, and AI reliability to minimize so-called false negatives/positives. When it comes to user acceptance it was generally good. After some initial hesitation motivated by the space limitations and difficulties fitting a computer and extra dashboards in the cabin, the crane operator realized the benefits and the performance of the system and took active part in the agile development and system realization. However, even though the test was successful, the scale-up and commercialisation took a halt after the test period ended. This was due to that no one in the ecosystem taking part in the test, including the main contractor, a digital tech consultant, an AI and cloud computing provider, the crane rental company, and the crane manufacturer, were willing to invest in the scale-up and commercialisation of the product.

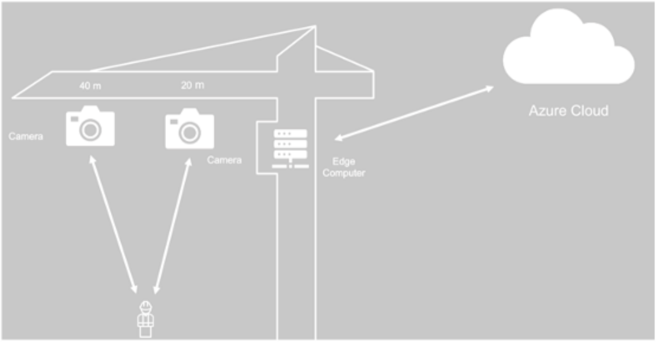

Figure 2: The setup of the crane camera case

Heavy machine IR cameras

As with site work in vicinity of crane operations, working close to heavy machines is one of the most dangerous work areas when it comes to severe and fatal accidents. Therefore, there is a need for a safety system warning both machine operators and workers for hazardous situations. This case employed an industrial-grade vision system that detects human workforce in the vicinity of the host vehicle and makes the driver and worker aware of a risk situation through visual and audible alarm signals. The main part of the system is an IR camera unit that is installed on a vehicle and that continuously monitors a defined risk area. The camera unit detects people with the help of the reflective properties of ordinary warning clothing, i.e., HVC and reflective vests, and assesses the distance between vehicle and person. If a worker is in the danger area, both the driver and the worker on site is alerted via an audio and light signal. The IR camera unit uses AI-powered vision technology and is stand-alone and does not need any internet connection while operating.

Figure 3: The setup of the case of IR cameras on heavy machines

The product is on the market, although it has not previously been used in construction. After the test period, the technical feasibility of the system was regarded high and worked without any malfunction during the test period, which included sunshine, darkness, rain, snow, ice, and dust. Like the crane operator, the machine operator was initially a bit sceptical, for similar reasons, but after some adjustments of the warning signals and setup in the vehicle cabin, the user acceptance was high. Also, the workers on site accepted the system almost immediately. The test involved the technology provider and a main contractor, employing an agile adjustment of an existing product. Generally, the results were positive, but the continual development got stuck. The technology provider did not want to invest the scale-up phase without sales guaranties, and the contractor did not want to invest in the scale-up but argued that it should be in the interest of the machine manufacturer or rental equipment company to invest and develop the system with the technology provider. Hence, no scale-up or commercialisation initiatives is currently going on.

Smart Helmets

On construction sites, workers can get hit and fall on the ground, waiting for someone to help them where risks of fatality increase with the time. Moreover, some accidents can be avoided by keeping workers away from certain danger zones during the day. To avoid these kinds of accidents, a new system was tested, which relies on a combination of technologies: Bluetooth beacons and a smart helmet (see *Figure 4*). The smart helmet is a helmet with a smart wearable IoT device that collects and reports data to a digital twin. The digital twin is a web-based collaboration application built around the IFC model. The system relies on three functions: (i) when the smart helmet detects a fall or hit, an internal alarm is being triggered, (ii) the localisation aided by the interaction between the smart helmet and Bluetooth beacons allow site management to identify the location of the personnel in danger, and (iii) the possibility for site management to define danger zones/restricted areas in the digital twin, which through the smart helmets and Bluetooth beacons warns personnel that are about to enter a zone.

Site management found the smart helmets and localisation functions useful and well-functioning. Danger zones were also found useful for protecting workers from dangerous areas. A further development was identified to use the digitally defined zones to increase productivity, for instance to avoid crowds in certain zones or to plan logistics better. However, there were technical (connection problems) and ergonomic (IoT device being large and heavy) issues with the smart helmets. For that reason, personnel placed the smart wearable on belts and pockets where they detected several false fall situations. Even though a successful test period, the contractor is not willing to use the helmet at its current state, wherefore the technology provider is investing in technological and ergonomic enhancements of the product. However, the contractor and the technology provider are working on an on-going project to develop the digital twin software and localisation functions further where also temperature, dust, noise and humidity sensors are deployed, and data is transferred to the digital twin.

Figure 4: The smart helmet with IoT device, Bluetooth beacons and digital twin.

Bluetooth communication technologies

Good quality communication between different work groups on construction sites is very important to avoid accidents. Considering that construction sites are noisy, and that most machines are well sound isolated, conventional communication methods such verbal communication and hand gestures become insufficient. Therefore, in this case commercially available Bluetooth headsets were tested in four rounds, where improvements were made to the Bluetooth headsets in each round. The improvements included localization warning and a natural interaction behaviour (NIB) function, which allows communication in noisy environments.

Construction workers reported that they were most satisfied with the headsets during first round, where their favourite form of communication shifted from verbal communication without headsets to telephone via Bluetooth headsets. Workers' satisfaction with the quality of communication with excavator operators, truck drivers and other personnel increased until the second round where localization warnings was introduced, followed by further decreasing satisfaction when the NIB function and combination of all functions were tested. Workers mostly complained about the cover range of Bluetooth headsets meaning that localization warnings and communication quality and noise cancellation functions were not working well in longer distances. The product is commercially available, without the additional functions tested in this case. Due to failures in technical aspects of developing the headsets, the construction contractor went back to using the original headsets and does not invest in any scale-up of new functions.

CONCLUSIONS

Table 1 summarizes the five case studies in terms of the digital safety technology employed and the findings.

Table 1: Overview of case studies and findings

	Digital safety technology			Case study findings and analysis		
Case	AI & vision system	Smart wearables & digital twins	Bluetooth communication	Technical feasibility	User acceptance	Scale-up & commercialisation
Safety equipment cameras	X			Good for helmet and HVC, with challenges for chinstrap and glasses.	Generally good on both individual and project level, with some hesitation related to integrity issues.	On-going. Scale-up test are running, and a rental equipment company plans to commercialise.
Crane IP cameras	X			Challenges in algorithm development, hardware and connectivity, AI reliability,	Initial issues with space limitations in crane cabin and notifications/ alerts, but then high acceptance.	Did not happen, due to that no one took lead responsibility, going from POC to production.
Heavy machine IR cameras	X			Available product tested in a new environment with good results.	Generally good and fast acceptance from both operators and workers.	Even though good test results, scale-up and commercialisation is halted.
Smart helmets and digital twin		X		Technical issues (connectivity, false alarms) with IoT device. Digital twin functionality worked well.	Challenges with heavy/large helmets. Digital twin, localisation and danger zone functionality were appreciated.	Smart helmets need functionality enhancements before scale-up. On-going projects to improve digital twin functionality.
Bluetooth headsets			X	Basic functionality worked well but limited long-range functions.	Workers preferred original headsets. Additional functions were not well accepted.	Original headsets are available in the market. No further investment in new functions.

The digital safety tools employed in the five cases differ in complexity, number of technologies and level of technology maturity. Yet, there were no direct links between complexity/technologies/maturity and the technical feasibility. Rather it is the contextual factors of the construction site environment that affect the feasibility (e.g., connectivity and signal range for IoT and communication tools and object detection and recognition algorithms not adjusted to site context). From a technical feasibility perspective all cases on a general level provided positive results, but also require further development to enhance user acceptance and prepare for scale-up and commercialisation.

The case findings show that user acceptance is generally good, but often after an initial hesitation. Hence, an iterative, agile approach has shown good results in the pilot testing of digital tools. In all but one case the iterations improved the product and the user acceptance. In the case where user acceptance decreased in each round of changes to the product, the reason was malfunctions in the technical feasibility and failure to resolve these issues. Similarly, the cases show the importance of making smart wearables easy to wear. If IoT devices, sensors, etc., are not seamlessly integrated for the intended use, the acceptance will be low.

The scale-up and possible commercialisation is difficult to analyse fully from the cases and pilot testing in this study. Rather, longitudinal studies would be preferable for covering the full commercialisation phase. However, the findings indicate that there is a long way from positive test results of the pilot testing to a decision for scale-up in the first phase and commercialisation in the second phase. Issues of investment, development costs and prospective sales and market penetration must be resolved through a cost-benefit analysis amongst the organisations participating in the ecosystems related to the digital tools and their future use.

In general, the focus is on safety, rather than productivity and quality, when it comes to digital technologies. The research in this field is somewhat fragmented and unstructured (Rao *et al.,* 2022). Real-time automated monitoring of construction sites, including real-time hazard identification, caring for workers' health and safety, is clearly a challenge (Rao *et al.,* 2022) and digital tools offer new possibilities for increasing site safety. This research contributes with case study findings on the actual use of digital tools in its intended, "real" environment at construction sites, but more research is needed. First and foremost, concerning technical feasibility and user acceptance of the digital tools, as well as how to scale-up and commercialise the digital tools. The latter involving both cost-benefit and ecosystem analyses.

REFERENCES

Arbetsmiljöverket (2019) *Arbetsmiljöstatistik: Dödsolyckor i arbetet orsak* (2010-2019), Available from: https://www.av.se/globalassets/filer/statistik/arbetsmiljostatistik-dodsolyckor-i-arbetet-orsak-2010-2019.pdf [Accessed 14 June 2021].

Arbetsmiljöverket (2021) *Arbetsskadestatistik* Available from: http://webbstat.av.se/QvAJAXZfc/opendoc.htm?document=accesspoint%5Carbetsskadestatistik.qvw&host=QVS%40vmextapp02-hk&anonymous=true&sheet=SH_Enkel [Accessed 14 June 2021].

Bause, K, Radimersky, A, Iwanicki, M and Albers, A (2014) Feasibility studies in the product development process, *Procedia CIRP*, 473-478.

Chauhan, C, Singh, A and Luthra, S (2021) Barriers to industry 4.0 adoption and its performance implications: An empirical investigation of emerging economy, *Journal of Cleaner Production*, **285**, 124809.

Chen, X, Chang-Richards, A Y, Pelosi, A, Jia, Y, Shen, X, Siddiqui, M K and Yang, N (2021) Implementation of technologies in the construction industry: A systematic review, *Engineering, Construction and Architectural Management*, [ahead of Print].

Davis, F D (1989) Perceived usefulness, perceived ease of use and user acceptance of information technology, *MIS Quarterly*, 13(3), 319-340.

Gholami, Y, Fredriksson, A, Rudberg, M and Simu, K (2019) Decoupling the delivery process in a construction supply chain employing a smart delivery container, *In*: *Proceedings from PLAN Fot Conference*, 23-24 October, 163-180.

Harmsen, J (2019) *Industrial Process Scale-Up: A Practical Innovation Guide from Idea to Commercial Implementation, 2nd Edition*, London: Elsevier.

Jacobsson, M and Linderoth, H C (2010), The influence of contextual elements, actors' frames of reference and technology on the adoption and use of ICT in construction projects: A Swedish case study, *Construction Management and Economics*, **28**(1), 13-23.

Mansoor, A, Liu, S, Ali, G M, Bouferguene, A and Al-Hussein, M (2020) Conceptual framework for safety improvement in mobile cranes, *In*: *Construction Research Congress 2020: Computer Applications*, Reston, VA: American Society of Civil Engineers, 964-971.

Park, J Kim, K and Cho, Y.K (2017) Framework of automated construction-safety monitoring using cloud-enabled BIM and BLE mobile tracking sensors, *Journal of Construction and Engineering Management*, **143**(2).

Qi, B, Razkenari, M, Costin, A, Kibert, C and Fu, M (2021) A systematic review of emerging technologies in industrialized construction, *Journal of Building Engineering*, **39**, 102265.

Rao, A S, Radanovic, M, Liu, Y, Hu, S, Fang, Y, Khoshelham, K, Palaniswami, M and Ngo, T (2022) Real-time monitoring of construction sites: Sensors, methods and applications, *Automation in Construction*, **136**, 104099.

Samuelsson, B (2019) Arbetsskador inom byggindustrin 2018: Bygg-och anläggning-privat sektor.

Sanni-Anibire, M O, Mahmoud, A S, Hassanain, M A and Salami, B A (2020), A risk assessment approach for enhancing construction safety performance, *Safety Science*, **121**, 15-29.

Sepasgozar, S M E, Loosemore, M and Davis, S R (2016), Conceptualising information and equipment technology adoption in construction, *Engineering, Construction and Architectural Management*, **23**(2), 158-176.

Sezer, A A and Bröchner, J (2019) Site managers' ICT tools for monitoring resources in refurbishment, *Engineering, Construction and Architectural Management*, **27**(1), 109-127.

Tsai, M (2009), Improving communication barriers for on-site information flow: An exploratory study, *Advanced Engineering Informatics*, **23**(3), 323-331.

Venkatesh, V, Morris, M G, Davis, G B and Davis, F D (2003) User acceptance of information technology: Toward a unified view, *MIS Quarterly*, **27**(3), 425-478.

Zhao, Z, Shen, L, Yang, C, Wu, W, Zhang, M and Huang, G.Q (2021) IoT and digital twin enabled smart tracking for safety management, *Computers and Operations Research*, **128**, 105183.