ARTICLES (PEER REVIEWED)

The Benefits and Challenges Associated with Technologies in Managing Workplace Health and Safety

Katrin Leifels[1],*, Julia Zeller-Lanzl[2], Azizur Rahman[3], Philipp Knoepfle[4], Brent Sandlant, Sascha Dreher, Stephan Dreyer

[1,3] RMIT University, School of Property, Construction and Project Management, PO Box 2476, Melbourne VIC, 3001, Australia, Orchid ID 0000-0001-9235-8090,

[2] University of Hamburg, Chair of Digital Innovation and Transformation, Vogt-Kölln-Straße 30, 22527 Hamburg, Germany, Orchid ID 0000-0002-5784-6926

[4] Ludwig-Maximilians-University, Department of Media and Communication, Akademiestr. 7, 80799 Munich, Germany, Orchid ID 0000-0003-3575-1229

Corresponding author: Katrin Leifels, Katrin.leifels@rmit.edu.au

Abstract

Digital technologies can enhance health and safety on construction sites. However, despite their benefits, only few of these technologies have been implemented. This study explores how construction health and safety stakeholders perceive the benefits and challenges associated with digital technologies to enhance health and safety on construction sites. Based on a literature review, digital technologies in the construction industry were categorised into nine distinct types, namely, Personal Communication Technologies, GPS-based Technologies, Planning & Simulation Tools, Visualisation Technologies, Training Programs, Wearables & Smart Tools, Additive Manufacturing, Robotics & Exoskeletons, and Vision-based Surveillance. Utilising semi-structured interviews, this research gathers insights into perceived benefits and challenges associated with these technologies from construction health and safety stakeholders, health and safety professionals, and construction specialised academic industry experts in Germany and Australia. Each type of technology was further analysed to understand its perceived benefits and obstacles. The findings indicate that some technologies offer significant benefits, notably in automating

construction processes and pre-emptively identifying potential incidents. However, the study also uncovers critical obstacles, particularly concerns about data protection and the financial burdens of development and implementation. This study provides unique insights into the perceptions of construction health and safety stakeholders regarding digital technologies. It highlights the dual nature of technology as a tool for advancement and a source of new challenges, specifically in terms of health and safety efficiency in the construction industry. The identification of specific benefits and obstacles offers a foundational understanding for further research and practical application in enhancing health and safety practices through digitalisation in construction.

Keywords

Digitalisation; Health; Safety; Digital Technologies; Robotics

Introduction

The construction industry is widely recognized as one of the most dangerous industries worldwide (Cheung & Zhang, 2020; Dobrucali, et al., 2024). In Germany, in 2023, 76 workers were killed in the construction industry (BG Bau, 2024), accounting for 20% of all worker fatalities in the private sector (DGUV, 2024). These numbers are high, considering that the construction industry only accounts for 5.8% of German employees (Destatis, 2024).

These numbers remain similar in other countries. In 2022, 27 fatalities occurred in the Australian construction industry, accounting for 14% of all fatalities (Safe Work Australia, 2023). In 2024, 17 construction workers were already killed at work in Australia by the 10th of October based on the preliminary worker deaths by industry or workplace (Safe Work Australia, 2024). These numbers highlight the global need to prevent occupational injuries and diseases.

Several papers indicate that digital technologies (DT) may be suitable for improving health (Jebelli, et al., 2018; Oke, et al., 2023; Zhang, et al., 2018) and safety (e.g., Fang, et al., 2018; Zhou, et al., 2015) in the construction industry. This is especially true for health and safety technologies and services, as most health and safety incidents can be traced back to hazardous exposures resulting from inadequacies in access to information, measurement technologies, and individual protective equipment and tools, all of which can be easily eliminated by DT (e.g., Omrany, et al., 2024).

However, despite the potential of digital technologies, the innovation potential of digital technologies has hardly been explored in the construction industry. Recent studies show that the use of digital technologies in the construction industry is still low (Dobrucali, et al. 2024) and that more evidence of its benefits is necessary before its promotion and implementation (Trask, & Linderoth 2023). This could be due to the fact that the construction industry is globally considered to be amongst the least digitised industries.

Whilst a variety of papers focus on the advantages and disadvantages of existing technologies (e.g., Yang, et al., 2020; Zhang, et al., 2020), this paper shifts its focus to the construction health and safety stakeholders' perceptions of digital technologies used on construction sites. Specifically, the authors aim to provide a better understanding of how construction health and safety stakeholders perceive potential benefits and obstacles that may be associated with digital technologies. The findings of this study will be used to provide a deeper understanding of the challenges associated with DT, which is crucial to identify underlying barriers that may hinder the implementation of DT. In addition, the authors aim to unfold the perceived benefits associated with DTS, which can be used to promote DTS and its implementation in the construction industry.

Digital technologies in the construction industry

The construction industry is a high-risk industry in terms of safety incidents and poor health (Cheung & Zhang, 2020; Dobrucali, et al., 2024). The working environment is characterised by fast reconfigurations of project setups and segmentation between planning and construction. This causes unsteady workflows, which is associated with high pressure due to time and cost considerations with high financial penalties for delays (Lingard, et al., 2015; Snashall, 2005; Vrijhoef & Koskela, 2000). In particular, workplace accidents are a threat to worker safety on construction sites. Many studies have been conducted to explore the relationship between poor health and safety in the construction industry. A study by Bentley, et al. (2006) investigated the key risk factors for construction slips, trips, and falls in residential buildings. They found that incidents on construction sites are often due to time pressure, excessively rapid movements, poor hazard perception, the need to divide attention, and fatigue.

Research suggests that digital technologies can help to improve health and safety (Oke, et al., 2023). Digital technologies include software applications and tools that convert analogue information to digital information using innovative tools and software applications (Oke, et al., 2023). For instance, global positioning systems (GPS) and smart sensors can be used to reduce vehicle accidents (Zhang, et al., 2018). In another example, very-high frequency active radio frequency can be used to warn on-foot construction workers and equipment operators in real time if any equipment gets too close to unknown or other existing equipment to prevent contact collisions that can threaten the safety and health of construction workers (Teizer, et al., 2010).

Construction workers are more exposed to musculoskeletal injury and physical strain than other industries such as retail trade, warehousing, and transport (Oakman, et al., 2019). These injuries occur frequently because of using heavy work tools, lifting heavy objects, or doing repetitive tasks for extended periods. Technology such as the exoskeleton reduces the strain and stress on a worker's body and muscle joints by supporting body posture and enhancing support during lifting. An unpowered exoskeleton distributes the lifting load to the performer's stronger muscle; thus, weaker muscles bear less weight for their safety. In addition, there are also powered exoskeletons available that use motors and sensors to help workers lift tasks or support awkward postures (Zhu, et al., 2021).

Whilst these technologies offer several benefits, criticism of the tools themselves and existing barriers persists. For instance, findings by Delegado, et al. (2019) from focus groups with 28 construction health and safety stakeholders and surveys highlight high implementation costs as the primary limiting factor for adopting robotics and automated systems. In addition, the fragmented nature of the construction industry makes it difficult to adopt innovative approaches (Oke, et al., 2024). Another technology that has revolutionised the construction industry is additive manufacturing. For instance, additive manufacturing of concrete, called 3D concrete printing, can significantly improve health and safety in this industry (Bos, et al., 2016) by reducing the worker's exposure to cement dust or overexertion. In addition, on-site sensor-based technology can be used to limit exposure to hazardous materials such as asbestos. These sensors can analyse environmental factors, such as humidity, temperature, air pollution levels, and UV light, by taking samples and analysing them. Site environmental conditions can then be visualised and monitored on Building Information Modelling (BIM), which can be used to monitor work and non-work zones in real time (Rao, et al., 2022). This technology allows users to track conditions, such as open shafts and edges, unsafe working heights, and unguarded machinery, and to control the workers' risk before incidents occur. However, this technology has also gained criticism. For instance, Boyd (2021) highlights that BIM, especially, can lead to a dangerous illusion by linking data and reality in the form of a problematic hyperreality. He points out that illusions may reduce the technical accuracy and are at risk to lead to a loss of meaning as well as a loss of perspective and control.

Other researchers, such as Dainty, et al. (2017), critique the ability to use BIM, especially for SMEs, and highlight several barriers. These include limited digital access and skills barriers and limited material and skills access, which are required for the ability and the development of skills to use the technology. Another concern is that digital technologies can also be used to substitute the physical presence of construction workers. Whilst this can be positive, for instance, for using drones equipped with vision-based surveillance systems and thermal imaging to detect safety issues, including leaks in high-risk or inaccessible areas on construction sites, it may also raise concerns. These concerns include fears amongst workers to be replaced or being continuously monitored. For instance, Brophy, et al. (2021) highlight that the implementation of robots, which are equipped with cameras and sensors, may invoke the feeling of being continuously monitored or watched, even though the robots may or may not use this technology. Moreover, Brophy, et al. (2021) highlight that this feeling can lead to anxiety and stress in workers.

The use of contemporary technologies and digital devices in construction has enhanced health and safety in this industry. However, it is also associated with uncertainty and barriers. Whilst there are a lot of studies analysing the general benefits and barriers associated with the implementation of these technologies, there is a lack of studies analysing how these technologies are perceived amongst construction health and safety stakeholders in practice. Our study aims to address this gap by interviewing construction health and safety stakeholders about their perceived benefits and challenges of these devices. In addition, this research will use a cross-country approach, where interviews will be undertaken with stakeholders in Germany and Australia.

Whilst numerous studies have explored the application of digital technologies, there is limited understanding of how construction health and safety stakeholders perceive these technologies in practice, including their perceived benefits, usability, and barriers to adoption. Existing studies are also largely context-specific, often focusing on single countries or technologies in isolation. This study addresses these gaps by adopting a qualitative cross-country approach to explore the perceptions of Health & Safety (H&S) stakeholders in Germany and Australia towards a variety of digital technologies identified through a literature review. In doing so, the research contributes to a more holistic understanding of the social and contextual factors shaping digital transformation in construction health and safety.

Methodological approach

The researchers used the databases Ebsco Host and ScienceDirect to identify relevant literature that focused on technologies promoting health in the construction industry. Keywords used were "digital," "health," "technology," "technologies," "service," "services," and "construction." The researchers identified 34 relevant studies published between 2000 and 2018 after reviewing titles, abstracts, and keywords. Each paper was assigned multiple tags related to the specific types of technology discussed in the paper, its area of application, and level of digitalisation.

These tags were then reviewed by three of the researchers, and they built the foundation of the development of the schemes using an inductive approach. Each theme was carefully reviewed to ensure it is distinct and does not overlap. Once all categories were created, two additional researchers reviewed the categories for clarity and distinctiveness to enhance the validity of the coding schemes. Once completed, the following nine categories for digital tools and technologies were created: (1) Personal Communication Technologies (PCTs), (2) GPS-based Technologies, (3) Planning & Simulation Tools, (4) Visualisation Technologies (VR/AR), (5) Training Programs, (6) Wearables & Smart Tools, (7) Additive Manufacturing, (8) Robotics & Exoskeletons, and (9) Vision-based Surveillance. The literature review and the development of nine categories were the first steps towards developing an interview guideline for a semi-structured interview. The aim of the interviews was to gather in-depth perceptions of the different types of technologies from construction health and safety stakeholders, using an exploratory qualitative approach. The interview guideline comprised four parts: introduction and professional background, personal

experience with H&S, an individual assessment of the nine pre-defined types of technologies, and an evaluation of digital technologies' future practicability. The individual assessment of digital technologies focused on the nine identified categories and evaluated their ability to improve health and safety on construction sites, along with potential associated benefits and challenges per category. Each interview partner was asked if they would consider working with those technologies. If participants were unfamiliar with a particular technology, a brief explanation was provided outlining its function and potential applications on-site. If the interview partners stated that they could not imagine working with a specific category of technologies, they were asked to provide a reason for their decision. The perceived future practicability of the devices was explored at the end of the interviews. The interview guidelines were used to enable the researchers to compare the content of interviews and to ensure reliability. The interviews were conducted as a two-stage process. The first interviews took place from November to December 2018 in Germany, and a second data collection through interviews was conducted from July to September 2019 in Australia. The interviews were conducted face-to-face or online using Skype. All participants were asked to actively provide written informed consent before the interviews commenced. Ethics for the collection of the Australian data was obtained [anonymised for the review process].

All the interviews were recorded with the participant's consent. To ensure reliability, the interviews were thematically coded using a deductive approach based on the predefined categories. Themes emerging from the interviews were categorised using the nine defined types of digital technologies and then subsequently into perceived benefits and challenges per type of technology. The coding of each interview was reviewed by a second researcher to ensure reliability.

SAMPLING AND PARTICIPANTS

The recruitment process was based on the guidelines of theoretical sampling (Urquhart, 2023). We aimed at diversifying our sample concerning gender, profession, and years of experience. In the first stage, seven experts from the German construction industry, including builders, foremen, H&S professionals, and construction managers, were interviewed. In the second stage, 10 experts in Australia were interviewed, including construction H&S professionals, project managers, and engineers. An overview of the participants per stage is presented in Table 1.

Table 1.   Interview participants.

Interviewee	Position	Area of expertise	Years of experience	Highest level of vocational training
#01	Student of civil engineering	On-site practical construction site experience; construction education and training	0 to 10	Diploma
#02	Apprenticeship in the field of heavy machinery (crane driver)	On-site practical construction site experience; construction administration experience; construction education and training	0 to 10	Diploma
#03	Head of sales	Construction industry; construction and digitalisation	0 to 10	Masters

Table 1. continued

Interviewee	Position	Area of expertise	Years of experience	Highest level of vocational training
#04	(Co-)Managing director of a mid-sized construction company	High level of (on-site) practical experience in the construction industry; construction management expertise	11 to 20	Masters
#05	Real estate consultant	Construction site management	0 to 10	Masters
#06	Senior consultant	Construction company management; digitalisation; process automation	0 to 10	Masters
#07	Research fellow	Academic digital technologies experience; practical experience in industrial and public construction projects	11 to 20	Masters
#08	OHS officer	High level of (on-site) practical experience; construction safety specialist; representative of industrial body (trade union)	30+	Diploma
#09	OHS–HSE manager	Construction safety specialist within a multinational construction company; high level of construction management knowledge and experience; experience with digital safety systems	30+	Masters
#10	OHS–HSE manager	High level of (on-site) practical experience; construction safety specialist; representative of industrial body (trade union)	30+	Ph.D.
#11	OHS–HSE Manager	High level of (on-site) practical experience; experience in safety management within a large construction industry subcontractor; experience with digital safety systems	11 to 20	Diploma
#12	Engineer	High level of (on-site) practical experience; construction management knowledge and experience within a small construction industry subcontractor	21 to 30	Graduate diploma

Table 1.   continued

Interviewee	Position	Area of expertise	Years of experience	Highest level of vocational training
#13	Project manager	Digital safety experience within residential and commercial fit-out sector; construction management experience	0 to 10	Diploma
#14	Engineer	Digital safety (design) specialist; experience within the civil construction sector	0 to 10	Bachelor
#15	OHS–HSE manager	International construction experience; digital safety experience; construction management experience	11 to 20	Masters
#16	Safety advisor	Construction safety experience within the property management sector	0 to 10	Graduate diploma
#17	OHS–HSE manager	Safety management experience within major construction industry bodies; experience with digital safety systems	0 to 10	Masters

Results

In the following, the perceived benefits and barriers associated with the implementation and use of the nine types of technologies are discussed per type. Further analysis revealed the main benefits and obstacles for each of the types of technologies.

PERSONAL COMMUNICATION TECHNOLOGIES

Most participants stated that a large fraction of construction workers actively work with Personal Communication Technologies such as smartphones. Its current designated application lies either in decentralised communication between individuals on construction sites or in private use. As a perceived main opportunity associated with personal communication technologies, participants highlight that this technology is already broadly available, yielding a fast adaptation and the opportunity to track employees in dangerous situations. For instance, participant 11 stated:

> "Say each individual person had a microchip on them that gave them their location or GPS, which mobile phones can do that and you're doing an evacuation, and there legitimately are people in the building and it's burning. It would work."

As the perceived main challenge, the participants raised concerns regarding data protection and privacy. Another issue is the governance of such tools, as participant 7 asserts:

> "[…] in the end, it is always up to the end user whether a technology is adopted; construction workers must see a clear benefit in its [Smartphone] use."

GPS-BASED TECHNOLOGIES

The second category focuses on GPS-based technologies. This type of technology automatically performs a spatial–temporal analysis of GPS-trackable key objects on-site. These may include workers, vehicles, equipment, payloads, and scaffolding. The perceived main opportunity towards health and safety associated with this technology is that GPS-based technologies can be employed to warn workers in more detail of hazardous zones via geo-positioning or could improve health and safety, by locating workers in an emergency. For instance, participant 10 stated:

> "in an emergency, to get people out, it [GPS] would be a good way to find out how many people are on-site and where they are and if there is an emergency to make sure everyone's out."

A perceived disadvantage associated with GPS-based technologies lies in the use of GPS data for monitoring individuals for management reasons rather than primarily as a health and safety tool. This can be highlighted by the following statement provided by participant 8 stating:

> "it [GPS] was masquerading as purely for health and safety but that it's been used as a management tool to monitor time and motion."

The constant feeling of being monitored via GPS by superiors can put more pressure on construction site workers, as voiced by participant 2. This holds especially true in countries such as Germany where data privacy is a very sensitive issue.

PLANNING & SIMULATION TOOLS

The third category includes planning and simulation tools. Planning tools are used in the planning and design stage of a construction project and thereby can help to avoid the occurrence of hazardous areas on the construction sites. When talking about the perceived main opportunities and challenges, participant 9 stated:

> "The use of a 3d or 4d model where you can fly through the building and visualise how you're going to do things, that has a massive impact, because you're actually doing that before you start the project. So, you analyse what are the risks; what's the control measures; what's the solutions."

Moreover, they state that digital planning and simulation tools can help in the identification of hazardous areas and the facilitation of safety communication. Participant 4, however, is concerned by the fact that planning and simulation tools are currently only accessible to large construction companies. Small- and medium-sized construction companies often do not have the financial resources to keep up with larger competitors. Another important challenge is the ability of these tools to simulate the construction environment. This can be illustrated with the following example provided by participant 10:

> "I don't think you can beat having hands-on experience and being mentored. But I think again, it could be used as a complement to, rather than a substitute for, having the hands-on experience […]. But when you get up in the real world […] I don't think you can simulate that pressure and stress that people get under because of timeframes and deadlines and real loads coming up with the simulation type thing."

VISUALISATION TECHNOLOGIES

The fourth category includes virtual reality (VR) and augmented reality (AR) tools to enhance visualisation. For example, VR, can be used "to describe a set of hardware and software technologies used to provide

interactive, real-time, 3D computer applications" ([Zhou, et al., 2012](), p. 105). These tools offer a variety of opportunities, such as the provision of context-aware information on invisible dangers and the ability to train workers in operating high-risk equipment and machinery. The use of VR as a training aid is supported by our participants as a highly positive opportunity that helps workers to become prepared to deal with potential risks in the operation of equipment and machinery in a virtual setting rather than dealing with it in real life from the beginning. For instance, participant 10 stated:

> "I think that it [VR] can be used as a complement to, rather than a substitute for having the hands-on experience."

Perceived challenges associated with visualisation technologies include (as previously alluded to) the no-risk sterile environment in which the VR exists. This can be highlighted by the following example from participant 10 in relation to VR for the training of tower crane drivers:

> "I don't think you can simulate the pressure and stress that people get under because of timeframes and deadlines and real loads coming up."

TRAINING PROGRAMS

The fifth category contains digital training programs, such as the virtual simulation training offered by the Master Builders of Victoria (Australia) via their Building Leadership Simulation Centre[1]. The major advantage associated with this type of training is the associated flexibility as it can be self-directed and, hence, focuses on the learner. For instance, participant 2 stated:

> "Safety instructions should take place often in order to keep regulations more present in the mind; particularly interesting are certain training in which certain behaviour patterns for dangerous situations are pre-trained, e.g. how do I behave if one of my colleagues gets a blow to the head."

Perceived disadvantages were the dependence on personal motivation and the blurring of the lines between the working and home environments. This is highlighted by the following quote from Participant 8:

> "I'm a big believer that the employer rents you eight hours a day; he doesn't own you. What you do in your personal time is your own business, and to have to take your own work home and then to have to sit up and do inductions at night … I don't think is equitable or fair."

WEARABLES & SMART TOOLS

The sixth category, Wearables & Smart Tools, focuses on tools that allow individuals to monitor their specific environment and receive feedback regarding potentially hazardous work practices. By recording data and providing feedback to the wearer, such tools can provide suggestions to prevent long-term health problems. For example, participant 11 stated:

> "If you had a one-stop device that was the size of a recorder and it slid into a Velcro little pocket on your top and you went about your daily business well that would be greatly beneficial to have all that data when you talk about how much noise [a] person being exposed to over an eight-hour work shift."

---

1   For further information about the Building Leadership Simulation Centre, please visit https://www.mbav.com.au/training/blsc.

The robustness of the devices, particularly their ability to remain fully functioning in the dusty and dirty construction environment, is perceived as the main challenge by our interviewees. For example, participant 10 stated:

> "The industry is very robust. And things get knocked around. So, the technology would have to be robust in itself to cope with the robustness of the industry. You couldn't have real sensitive scientific instruments because we know on a building site, they'd probably last a day, and they'd get knocked and pushed and thrown back in the box."

In addition, some participants highlighted that it was difficult to deal with the interruption to the workers' workflow that the tools caused with their recommendations. One participant (4) was hesitant towards the introduction of such tools clashing with existing hierarchies:

> "I can't imagine how that would work with the equipment [wearables & smart tools] […], we have the foreman on the site who should and must take on this role of looking after workers and telling them when and where to take breaks, etc."

ADDITIVE MANUFACTURING

Additive manufacturing is the process of converting information from a computer-aided design (CAD) file to a stereolithography (STL) file (Wong & Hernandez, 2012). This process allows for the automation of steps of the construction process and can help potential risks and incidents faced by workers before they occur. For instance, participant 14 stated:

> "I'm working on a project where we've got a full federated model for what we're building so [..] you're able to stand around it and look at construction issues and deep pits where things are clashing where they're going to have utility clashes which you're not aware that it's a clash until you're able to see it visually […] if you're able to, sometimes seeing things visually is more important than seeing things in a 2D view."

This quote aligns with a statement provided by participant 9 who referred to the advantage of identifying incidents pre-emptively. He stated:

> "When you use 3D or a 4D model where you can actually fly in through the building and visualise how you're going to do things, that has a massive impact, because you're actually doing that before you even start the project."

The requirement for new knowledge was perceived as an obstacle associated with additive manufacturing. This can also be highlighted by the following quote:

> "I think a lot of the obstacles we're seeing is the training is not there so the employees aren't ready to use these products and the products themselves aren't ready to be used" (participant 14).

Another challenge associated with additive manufacturing is the potential resistance to change in the construction industry. For example, participant 16 stated:

> "The main obstacle I see at the moment is people wanting to actually [sic] implement it and do it. It does mean a complete overhaul with how the industry currently runs; people don't like change, they're scared of losing jobs, what the different risks are with using those kinds of technologies."

ROBOTICS & EXOSKELETONS

These technologies allow the facilitation of heavy physical work, especially for a handicapped and ageing workforce. The opportunity to relieve body stress injuries (BSIs) associated with heavy physical work was perceived as a major advantage, whilst the competition with existing vehicles and tools was perceived as a challenge. For example, participant 4 stated:

> "63 per cent of our injuries are muscular-skeletal repetitive strain injuries, hurry hurry, rush rush, get it up there quick come on let's go. So, I've seen recently a device that you strap to your knees…. so if you kneel down it helps you stand up again."

The main obstacle raised was the costs associated with the design development and introduction of the technology, especially for small enterprises. This can be highlighted by the following quote from participant 11:

> "[A] man in a van running his refrigeration business with an apprentice if you're going to enforce some digital compliance on them, that will cost. You're going to find someone like the apprentice without a job."

VISION-BASED SURVEILLANCE

The last category contains vision-based surveillance, such as video cameras. The main advantage associated with this technology is the associated costs as it is very affordable. Associated obstacles with this technology are privacy and data protection concerns. For instance, participant 2 stated:

> "Surveillance techniques are rather unsuitable for countries like Germany due to data protection concerns shared by the general public."

Participant 5 voiced additional concerns regarding worker privacy:

> "It [vision-based surveillance] can certainly help to get people to wear their helmets, but privacy-wise it's a mess and could never be enforced on German construction sites."

To summarise our findings, Table 2 provides an overview of the main opportunities and perceived challenges of the different digital technologies categories.

OUTLOOK FOR THE FUTURE USE OF THESE TECHNOLOGIES

The interview partners also provided an outlook on the future use of digital technologies. Participants acknowledged that digital technologies are able to improve health and safety on construction sites; however, they highlighted that costs are a big concern when it comes to the implementation as well as usage of these technologies. For instance, one participant highlighted that health and safety are important, but noted that, in practice, health and safety of the individual workers is often not prioritised. They further perceived the costs associated with the implementation of new technologies as a major barrier. Participants acknowledged high implementation costs as a key barrier to adopting new technologies. Nevertheless, they suggested that adoption is facilitated when costs are reasonable and when technologies contribute to shorter working hours and improved health and safety without generating new challenges during the construction process.

Furthermore, some participants also expressed concerns that the use of new technologies may diminish individuals' ability to think holistically, suggesting that this capacity could further decline over time as technological reliance increases. Related to these concerns on cognitive impacts, some participants also pointed to concerns about privacy. They were worried that, over time, awareness of the importance of privacy could decline as new technologies become more deeply embedded in everyday work practices.

Table 2. Main opportunities and challenges for the nine digital health categories.

Category	Main opportunity	Main challenge
Personal Communication Technologies	Hardware that is already broadly available, yielding a fast adaptation.	Extensive interconnection between multiple individuals causes privacy and data protection concerns.
GPS-based Technologies	Automatic spatial–temporal analysis of various objects on site. Locating people and machinery on large sites across vast terrains.	Restriction to motion- and position-related dangers. Tracking workers for non-safety related reasons (time motion style studies).
Planning & SimulationTools	Anticipation and avoidance of hazardous areas. Creating the ability to remove hazards at the preliminary design stage.	A broad variety of site-specific technical data and geo-information is required. Education and training are needed to upskill the current workforce to enable the effective use of such tools.
Visualisation Technologies (VR/AR)	Provide context-aware information on invisible dangers.	Avoidance of visual impairment and stimulus overload.
Computer-based Training Programs	Self-directed, learner-focused training.	Dependence on personal motivation and repetition.
Wearables & Smart Tools	Behavioural suggestions to prevent long-term health problems.	Potentially perceived interruption of workflow and incentivise healthy usage. Robustness of devices and technology particularly in the dusty and dirty construction environment.
Additive Manufacturing	Automation of steps of the construction process and identification of incidents before they occur	Acceptance of builders and new knowledge requirements.
Robotics & Exoskeletons	Facilitation of heavy physical work, especially for a handicapped and ageing workforce. Relieving body stress injuries (BSIs) associated with heavy physical work.	Competition with existing vehicles and tools, no impedance of individual mobility of workers. The cost associated with the design development and introduction of the technology in an industry dominated by small enterprises.
Vision-based Surveillance	Technologically affordable automated check of compliance with basic safety regulations.	Major privacy and data protection concerns

Participants generally agreed that the construction industry is likely to face increasing pressure to integrate new technologies and digital solutions in the future. They observed that digital tools such as BIM are already becoming standard in certain processes, whilst automation is expected to play an even greater role in the coming years. At the same time, participants highlighted the potential of technological integration to support worker well-being, for example, by linking systems that monitor stress or provide early warning functions.

Differences between the Australian and the German sample

Participants in Germany highlighted that the German construction industry's innovation capacity is generally quite low. This, in turn, affects the implementation of new technologies, as the infrastructure necessary for these technologies does not exist in the construction industry.

Another important difference between the German and the Australian sample concerned privacy-related issues amongst German participants. The constant feeling of being monitored via GPS by superiors was described as a potential source of additional pressure on construction site workers. This concern appears particularly pronounced in countries such as Germany where data privacy is a very sensitive issue as compared to other countries (see, for instance, Ilhan & Fietkiewicz, 2021). This observation aligns with findings by Shanley, et al. (2023), who reported that Australians, on the other hand, seem not to be too concerned about privacy as much, using the case that Australians seem to be unconcerned about surveillance in public and private spaces.

A further concern expressed by German participants related to safety standards, which can partly be undermined by subcontractors from other European Union countries, with lower regulatory requirements. In Australia, construction companies also use many subcontractors; however, Australian-specific Health and Safety legislation must still be met.

Overall, participants from both countries appeared generally open to the adoption of new technologies.

Discussion and implications

This study aimed to investigate the perceived benefits and obstacles associated with the adoption of digital technologies in the construction industry. Based on the interviews, digital technologies were categorised into nine types: Personal Communication Technologies, GPS-based Technologies, Planning & Simulation Tools, Visualisation Technologies (VR/AR), Training Programs, Wearables & Smart Tools, Additive Manufacturing, Robotics & Exoskeletons, and Vision-based Surveillance. The following discussion presents a synthesis of the main findings for each type of technology and their implications for the construction industry.

PCTs are widely available and have the potential to improve health and safety in the construction industry by facilitating decentralised communication and tracking employees in dangerous situations (Aiyewalehinmi, 2013). However, concerns about data protection and privacy may limit their widespread adoption (Adams, 2017). Participants also raised concerns about data protection, privacy, and the governance of these tools. As participant 7 highlights, construction workers must see a clear benefit in using such technologies, suggesting that the success of their implementation depends on end-user acceptance. Balancing privacy concerns with the potential benefits of these technologies remains a critical challenge for the construction industry as it moves towards increased digitisation and the adoption of new technologies. Moreover, the successful implementation of PCTs depends on the perceived benefits and willingness of construction workers to use them (Gambatese, et al., 2008).

GPS-based technologies offer several opportunities for enhancing health and safety on construction sites, such as detailed hazard warnings and locating workers in emergencies (Park, 2017; Teizer, et al.,

2013). However, their use for monitoring individuals' performance rather than health and safety can lead to increased pressure on construction workers and may hinder their adoption, particularly in countries with strict data privacy laws (Bernhardt, et al., 2023). A significant challenge associated with GPS-based technologies is their potential misuse for monitoring individuals for management purposes rather than as a primary health and safety tool. Participant 8's statement underlines this concern, suggesting that GPS technology may be perceived as "masquerading as purely for health and safety" whilst, in reality, being used as a management tool to monitor time and motion. This constant feeling of being monitored may put additional pressure on construction workers, as voiced by participant 2. Data privacy concerns are particularly salient in countries like Germany, where privacy is a sensitive issue.

Planning and simulation tools can help identify and mitigate potential hazards during the design phase of a construction project (Sacks, et al., 2013). These tools can also facilitate safety communication amongst stakeholders (Zhang, et al., 2015). Moreover, these tools can help identify hazardous areas and facilitate safety communication, as noted by participant 9, who stated that 3D or 4D models could allow for a detailed analysis of risks and control measures before a project commences. However, their adoption may be limited to large construction companies, as small- and medium-sized enterprises often lack the financial resources and expertise required to utilize these tools effectively (Vidalakis, et al., 2020). Additionally, the ability of planning and simulation tools to replicate real-world construction environments may be limited, as suggested by participant 10. Hands-on experience and mentoring remain essential components of training, with simulation tools acting as a complement rather than a substitute. Factors such as crane sway, the presence of other buildings, and the pressure and stress that workers face due to tight deadlines cannot be fully simulated, underscoring the importance of maintaining a balance between virtual training and hands-on experience.

Visualisation technologies, including VR and AR, can provide context-aware information on invisible hazards and train workers in operating high-risk equipment in a safe, virtual setting (Wang, et al., 2018). However, the sterile environment of VR may not fully simulate real-world pressures and stressors experienced by construction workers, limiting its effectiveness as a stand-alone training tool (Gheisari & Esmaeili, 2019). Participant 10 pointed out the limitations of VR in simulating the pressure and stress that workers face due to tight deadlines and actual loads during real-life operations, particularly when training tower crane drivers. Visualisation technologies such as VR and AR can provide valuable training opportunities and enhance health and safety in the construction industry. However, it is important to recognise their limitations and ensure they are used as a complement to real-life, hands-on experiences.

Digital training programs offer flexible, learner-focused alternatives to traditional training methods (Yankov, et al., 2021). However, their success depends on individual motivation, and some participants expressed concerns about the blurring of work and personal boundaries associated with online training, which aligns with findings by Stary and Weichhard (2012). Digital training programs offer flexibility and can be self-directed, allowing learners to focus on areas relevant to their needs. As participant 2 mentioned, frequent safety instructions and training can help improve behaviour patterns in dangerous situations. However, there are also perceived disadvantages associated with digital training programs. One concern is the dependence on personal motivation, as the effectiveness of these programs relies on the individual's willingness to engage with the content. Additionally, the blurring of lines between work and home environments can be problematic. Participant 8 emphasised the importance of maintaining a balance between personal and work life, expressing concerns about the fairness of requiring workers to complete training during their personal time. Digital training programs can provide valuable learning opportunities and enhance health and safety in construction. However, it is crucial to consider their potential drawbacks, such as dependence on personal motivation and the potential intrusion into personal time. Employers should aim to strike a balance that respects employees' personal lives whilst ensuring effective safety training.

Wearables & Smart Tools can monitor workers' health and provide feedback on potentially hazardous practices (Awolusi, et al., 2018). However, the durability of these devices in the construction environment and their potential to disrupt workers' workflows are key challenges to their adoption (Gao, et al., 2022). Additionally, participants raised concerns about the potential for these tools to clash with existing hierarchies on construction sites. These tools can help to prevent long-term health problems by recording data and providing suggestions, as noted by participant 11. There are challenges associated with the adoption of Wearables & Smart Tools in the construction industry. One major concern is the robustness of the devices, as they need to withstand the harsh construction site environment. Participant 10 emphasised the importance of having durable and resilient technology that can cope with the industry's demands. Another issue raised by the participants is the potential interruption to workers' workflow caused by the tools and their recommendations. Furthermore, participant 4 expressed concerns regarding the introduction of such tools conflicting with existing hierarchies on construction sites, as the role of monitoring workers and ensuring their well-being often falls under the responsibility of a foreman. Wearables & Smart Tools offer promising opportunities to enhance health and safety in construction. However, addressing the challenges of device robustness and integration into existing workflows and hierarchies is crucial for their successful implementation.

Additive Manufacturing can automate aspects of the construction process, reducing potential risks and incidents (Ford & Despeisse, 2016). However, the adoption of additive manufacturing technologies may be hindered by the need for new knowledge and resistance to change within the industry (Alves, et al., 2023; Ford & Despeisse, 2016). Participant 14's statement emphasises the value of visualising clashes and potential hazards in a 3D environment, whilst participant 9 highlights the importance of using 3D or 4D models to identify risks and develop control measures before a project begins. However, the adoption of additive manufacturing in the construction industry faces challenges. One major hurdle is the requirement of new knowledge and training for employees, as noted by participant 14. This implies that a lack of adequate training and preparation may hinder the effective implementation of additive manufacturing technologies. Another challenge is the potential resistance to change within the construction industry. Participant 16 points out that implementing additive manufacturing may require a complete overhaul of current industry practices, which could be met with resistance from stakeholders who fear job loss and are uncertain about the risks associated with these technologies. Additive manufacturing holds significant potential for improving construction health and safety by automating processes and identifying hazards early on. However, addressing the challenges of employee training and industry resistance to change is crucial for successful implementation.

Robotics & Exoskeletons can facilitate heavy physical work, especially for an ageing workforce, and help to alleviate body stress injuries associated with manual labour (Cho, et al., 2018). However, the cost of these technologies and the need for specialised training may limit their adoption, particularly for small- and medium-sized construction companies (Okpala, et al., 2022). Furthermore, concerns about potential job losses and the deskilling of the construction workforce may lead to resistance from employees and labour unions (Sherratt, et al., 2020). Participant 4's statement emphasises the potential of exoskeleton technology to help workers avoid repetitive strain injuries, which account for a significant proportion of construction-related injuries. However, the adoption of robotics and exoskeletons also presents challenges, particularly in terms of costs and competition with existing tools and vehicles. Small enterprises may struggle to bear the financial burden of implementing these technologies, as noted by participant 11. This suggests that careful consideration should be given to the potential impact of enforcing digital compliance on small businesses and their workforce. Robotics and exoskeletons offer promising opportunities for improving construction health and safety by easing the physical workload on workers and reducing the risk of BSI. Nevertheless, addressing the challenges associated with cost and competition with existing equipment is essential to ensure the successful integration of these technologies in the construction industry.

Vision-based surveillance systems can monitor worksites in real time, identifying potential hazards and alerting workers to imminent dangers (Yang, et al., 2014). However, the accuracy of these systems may be limited by environmental factors such as poor lighting and variable weather conditions, as well as the complexity of construction sites (Wang, et al., 2021). Additionally, concerns about privacy and the potential misuse of surveillance data may hinder the adoption of these systems (Welbourne, et al., 2007). Participants 2 and 5 emphasise the difficulties of implementing vision-based surveillance in such contexts, where privacy issues may outweigh the potential safety benefits. To address these concerns, construction companies need to adopt surveillance technologies that strike a balance between safety and privacy. Additionally, creating clear policies and guidelines on the use of vision-based surveillance technologies can help ensure that worker privacy is respected whilst maintaining health and safety standards on construction sites. Whilst vision-based surveillance offers an affordable solution for enhancing construction health and safety, it is crucial to consider privacy and data protection concerns in its implementation. By addressing these challenges, the construction industry can benefit from the advantages of this technology without compromising worker privacy.

The adoption of digital technologies offers numerous opportunities to improve the construction industry's safety record. However, challenges such as cost, privacy concerns, resistance to change, and the need for specialised training must be addressed to facilitate widespread implementation.

Our study found differences between the German and Australian participants, especially regarding data and privacy concerns. This finding aligns with a study conducted by Schroeder, et al. (2024) that compared Australian and German attitudes towards privacy concerns on the use of mobile health apps as a case study. In their study, the researchers compared German and Australian users regarding their concerns using mobile health apps and found statistically significant differences between the two countries regarding concerns with data sharing. Similar to this study, the German participants were more concerned about the information being shared with their insurance provider or an independent service provider as compared to the Australian participants.

Limitations

Our study has limitations due to its qualitative research design and the sampling. Even though we aimed at reducing the risks of geographical bias by interviewing experts from Germany and Australia, the small sample size restricts the generalisation of our findings. Even though interviews are open to bias, the subjective perception from the standpoint of the interview partners is crucial for attributing meaning to experience (Hammarberg, et al., 2016). Therefore, this should not be categorised as a limitation.

One of the limitations of this research is the sample used. Although participants came from different cultural backgrounds, the results may have been influenced by the cultural background of the participants, being mainly a relatively high number of Australian and German participants. Even though Australians and Germans are very close in some dimensions such as power distance and masculinity, they score very differently in their long-term orientation (Australia, 21; Germany, 83) (Hofstede, et al., 2010). Long-term orientation describes how a society deals with challenges of the present and future, whilst maintaining links with their past. Australia's society can be described as a normative culture, which is characterised by focusing on achieving quick results and a small propensity to save for the future. Germany's society, on the other hand, can be described as pragmatic. Pragmatic societies have a strong propensity to invest and perseverance in achieving results (Hofstede, et al., 2010).

It cannot be excluded that these differences in the long-term orientation may have affected the results of this study. To address this, future research should aim for a larger sample and one with participants from a broader range of cultural backgrounds. We believe that a larger sample of interviewees will help in gaining a broader understanding of the current perceptions of digital technologies in the construction industry.

In particular, the inclusion of more construction workers and employees working directly in H&S, such as H&S officers, would enable a wider spectrum of opinions and more detailed expert knowledge. Future work should focus on elaborating thoroughly on the advantages and challenges of digital technologies in the construction industry and develop strategies for a meaningful introduction to digital technologies. Further, many issues that come across with the use of digital technologies, such as job alienation and factors potentially causing technostress (e.g., job insecurity and information overload), will only appear when digital technologies have already been used for a longer period. Thus, future research should closely accompany the implementation of these technologies and analyse their effectiveness and consequences.

Conclusion

The results of this study showed that digital technologies can be categorised into nine types. Each of them offers unique benefits that can enhance construction workers' health and safety. However, the findings also included obstacles that may hinder the implementation of these technologies. Specifically, our results show that digital technologies offer significant benefits, notably the ability to provide context-aware information, behavioural suggestions to prevent long-term health problems, the automation of steps in the construction process, and the identification of incidents before they occur. Critical obstacles were identified in the form of privacy and data protection concerns, new knowledge requirements, and costs associated with the implementation of digital health technologies. When promoting digital health technologies, organisations should not only focus on the associated benefits. Organisations must also address workers' concerns in order to implement digital technologies successfully.

References

Adams, M. (2017), "Big data and individual privacy in the age of the internet of things". Technology Innovation Management Review, 7(4), 12–24. https://doi.org/10.22215/timreview/1067

Aiyewalehinmi, E. O. (2013), "Factor analysis of communication in the construction industry", The International Journal of Engineering and Science, 2(10), 49–57.

Alves, J. L., Santana, L., & Rangel, B. (2023), "4d printing and construction: Reality, future, or science fiction?" In B. Rangel, A. S. Guimarães, J. Lino, & L. Santana (Eds.), 3D Printing for Construction with Alternative Materials (pp. 155–175). Springer, Cham. https://doi.org/10.1007/978-3-031-09319-7_7

Awolusi, I., Marks, E., & Hallowell, M. (2018), "Wearable technology for personalized construction safety monitoring and trending: Review of applicable devices", Automation in Construction, 85, 96–106. https://doi.org/10.1016/j.autcon.2017.10.010

Bentley, T. A., Hide, S., Tappin, D., Moore, D., Legg, S., Ashby, L., & Parker, R. (2006), "Investigating risk factors for slips, trips and falls in New Zealand residential construction using incident-centred and incident-independent methods", Ergonomics, 49(1), 62–77. https://doi.org/10.1080/00140130612331392236

Bernhardt, A., Kresge, L., & Suleiman, R. (2023), "The data-driven workplace and the case for worker technology rights", ILR Review, 76(1), 3–29. https://doi.org/10.1177/00197939221131558

BG Bau (Ed.). (2024), "Pressemappen zu den Jahreszahlen" [Press kits for the annual figures]. https://www.bgbau.de/die-bg-bau/presse/presseportal/pressemappen/pressemappe-zu-den-jahreszahlen-2023

Bos, F., Wolfs, R., Ahmed, Z., & Salet, T. (2016), "Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing", Virtual and Physical Prototyping, 11(3), 209–225. https://doi.org/10.1080/17452759.2016.1209867

Boyd, D (2021), "A critical inquiry into the hyperreality of digitalization, construction", Construction Management and Economics, 39(7), 549–564, https://doi.org/10.1080/01446193.2021.1904515

Brophy, P., Albeaino, G., Gheisari, M., & Jeelani, I. (2021), "New risks for workers at heights: Human-drone collaboration risks in construction", Computing in Civil Engineering, 2021. 321-328. https://doi.org/10.1061/9780784483893.040

Cheung, C. M., & Zhang, R. P. (2020), "How organizational support can cultivate a multilevel safety climate in the construction industry", Journal of Management in Engineering, 36(3), 4020014. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000758

Cho, Y. K., Kim, K., Ma, S., & Ueda, J. (2018), "A robotic wearable exoskeleton for construction worker's safety and health", in C. Wang, C. Harper, Y. Lee, R. Harris, & C. Berryman (Eds.), Construction Research Congress 2018 (pp. 19–28). American Society of Civil Engineers. https://doi.org/10.1061/9780784481288.003

Dainty, A., Leiringer, R., Fernie, S., & Harty, C. (2017), "BIM and the small construction firm: a critical perspective." Building research & information, 45(6), 696-709. https://doi.org/10.1080/09613218.2017.1293940

Destatis (Ed.). (2024), „Erwerbstätige und Arbeitnehmer nach Wirtschaftsbereichen (Inlandskonzept) 1 000 Personen", https://www.destatis.de/DE/Themen/Arbeit/Arbeitsmarkt/Erwerbstaetigkeit/Tabellen/arbeitnehmer-wirtschaftsbereiche.html

DGUV (Ed.). (2024), „Tödliche Arbeitsunfälle", https://www.dguv.de/de/zahlen-fakten/au-wu-geschehen/toedliche-au/index.jsp?query=webcode+d35030

Dobrucali, E., Sadikoglu, E., Demirkesen, S., Zhang, C., Tezel, A., & Kiral, I. A. (2024), "A bibliometric analysis of digital technologies use in construction health and safety", Engineering, Construction and Architectural Management, 31(8), 3249–3282. https://doi.org/10.1108/ECAM-08-2022-0798

Fang, Q., Li, H., Luo, X., Ding, L., Luo, H., Rose, T. M., & An, W. (2018), "Detecting non-hardhat-use by a deep learning method from far-field surveillance videos", Automation in Construction, 85, 1–9. https://doi.org/10.1016/j.autcon.2017.09.018

Ford, S., & Despeisse, M. (2016), "Additive manufacturing and sustainability: An exploratory study of the advantages and challenges", Journal of Cleaner Production, 137, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150

Gambatese, J. A., Behm, M., & Rajendran, S. (2008), "Design's role in construction accident causality and prevention: Perspectives from an expert panel, "Safety Science, 46(4), 675–691, https://doi.org/10.1016/j.ssci.2007.06.010

Gao, R., Mu, B., Lyu, S., Wang, H., & Yi, C. (2022), "Review of the application of wearable devices in construction safety: A bibliometric analysis from 2005 to 2021", Buildings, 12(3), 344. https://doi.org/10.3390/buildings12030344

Gheisari, M., & Esmaeili, B. (2019), "PARS: Using augmented panoramas of reality for construction safety training", https://www.cpwr.com/wp-content/uploads/publications/ss2019-pars-construction-safety-training.pdf

Hammarberg, K., Kirkman, M., & Lacey, S. de (2016), "Qualitative research methods: When to use them and how to judge them", Human Reproduction, 31(3), 498–501. https://doi.org/10.1093/humrep/dev334

Hofstede, G., Hofstede, G. J., & Minkov, M. (2010), Cultures and organizations: Software of the mind : Intercultural cooperation and its importance for survival, (Revised and expanded third edition). McGraw-Hill.

Ilhan A., & Fietkiewicz K.J. (2021), "Data privacy-related behavior and concerns of activity tracking technology users from Germany and the USA". Aslib Journal of Information Management, 73(2) 180–200, doi: https://doi.org/10.1108/AJIM-03-2020-0067

Jebelli, H., Hwang, S., & Lee, S. (2018), "EEG-based workers' stress recognition at construction sites," Automation in Construction, 93, 315–324. https://doi.org/10.1016/j.autcon.2018.05.027

Lingard, H., Peihua Zhang, R., Blismas, N., Wakefield, R., & Kleiner, B. (2015), "Are we on the same page? Exploring construction professionals' mental models of occupational health and safety", Construction Management and Economics, 33(1), 73–84. https://doi.org/10.1080/01446193.2015.1016541

Oakman, J., Clune, S., & Stuckey, R. (2019), "Work-related musculoskeletal disorders in Australia", https://www.safeworkaustralia.gov.au/system/files/documents/1912/work-related_musculoskeletal_disorders_in_australia_0.pdf

Oke, A.E., Aliu, J., Fadamiro, P., Jamir Singh, P.S., Samsurijan, M.S. & Yahaya, M. (2024), "Robotics and automation for sustainable construction: microscoping the barriers to implementation", Smart and Sustainable Built Environment, 13(3), 625-643. https://doi.org/10.1108/SASBE-12-2022-0275

Oke, A. E., Aliu, J., Jamir Singh, P. S., Onajite, S. A., Shaharudin Samsurijan, M., & Azura Ramli, R. (2023), "Appraisal of awareness and usage of digital technologies for sustainable wellbeing among construction workers in a developing economy", International Journal of Construction Management, 1–9. https://doi.org/10.1080/15623599.2023.2179628

Okpala, I., Nnaji, C., Ogunseiju, O., & Akanmu, A. (2022), "Assessing the role of wearable robotics in the construction industry: Potential safety benefits, opportunities, and implementation barriers", in H. Jebelli, M. Habibnezhad, S. Shayesteh, S. Asadi, & S. Lee (Eds.), Automation and robotics in the architecture, engineering, and construction industry (pp. 165–180). Springer International Publishing. https://doi.org/10.1007/978-3-030-77163-8_8

Omrany, H., Mehdipour, A., & Oteng, D. (2024), "Digital twin technology and social sustainability: Implications for the construction industry", Sustainability, 16(19), 8663. https://doi.org/10.3390/su16198663

Park, J. W. (2017), "Tracking for worker safety assessment", Georgia Institute of Technology. https://smartech.gatech.edu/handle/1853/60110

Rao, A. S., Radanovic, M., Liu, Y., Hu, S., Fang, Y., Khoshelham, K., Palaniswami, M., & Ngo, T. (2022), "Real-time monitoring of construction sites: Sensors, methods, and applications", Automation in Construction, 136, 104099. https://doi.org/10.1016/j.autcon.2021.104099

Sacks, R., Perlman, A., & Barak, R. (2013), "Construction safety training using immersive virtual reality", Construction Management and Economics, 31(9), 1005–1017. https://doi.org/10.1080/01446193.2013.828844

Safe Work Australia (Ed.). (2023), "Key work health and safety statistics, Australia 2023", https://data.safeworkaustralia.gov.au/insights/key-whs-stats-2023

Safe Work Australia (Ed.). (2024), "Preliminary fatalities". https://data.safeworkaustralia.gov.au/interactive-data/topic/preliminary-fatalities-2024

Shanley A, Johnstone M, Szewczyk P, Crowley M (2023), "An exploration of Australian attitudes towards privacy". Information and Computer Security, 31(3) 353–367, https://doi.org/10.1108/ICS-11-2022-0171

Sherratt, F., Dowsett, R., & Sherratt, S. (2020), "Construction 4.0 and its potential impact on people working in the construction industry", Proceedings of the Institution of Civil Engineers - Management, Procurement and Law, 173(4), 145–152. https://doi.org/10.1680/jmapl.19.00053

Snashall, D. (2005), "Occupational health and safety in the construction industry", Scandinavian Journal of Work, Environment & Health, 31, 5–10.

Stary, C., & Weichhard, G. (2012), "An e-learning approach to informed problem solving", Knowledge Management & E-Learning: An International Journal, 4(2), 195–216. https://www.researchgate.net/profile/chris-stary/publication/227943372_an_e-learning_approach_to_informed_problem_solving/links/0deec52b09c6593f3c000000/an-e-learning-approach-to-informed-problem-solving.pdf

Teizer, J., Allread, B. S., Fullerton, C. E., & Hinze, J. (2010), "Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system", Automation in Construction, 19(5), 630–640. https://doi.org/10.1016/j.autcon.2010.02.009

Teizer, J., Cheng, T., & Fang, Y. (2013), "Location tracking and data visualization technology to advance construction ironworkers' education and training in safety and productivity", Automation in Construction, 35, 53–68. https://doi.org/10.1016/j.autcon.2013.03.004

Urquhart, C. (2023), Grounded theory for qualitative research: A practical guide (Second edition). SAGE.

Vidalakis, C., Abanda, F. H., & Oti, A. H. (2020), "BIM adoption and implementation: Focusing on SMEs", Construction Innovation, 20(1), 128–147. https://doi.org/10.1108/CI-09-2018-0076

Vrijhoef, R., & Koskela, L. (2000), "The four roles of supply chain management in construction", European Journal of Purchasing & Supply Management, 6(3-4), 169–178. https://doi.org/10.1016/S0969-7012(00)00013-7

Wang, P., Wu, P., Wang, J., Chi, H.-L., & Wang, X. (2018), "A critical review of the use of virtual reality in construction engineering education and training", International Journal of Environmental Research and Public Health, 15(6). https://doi.org/10.3390/ijerph15061204

Wang, Z., Zhang, Q., Yang, B., Wu, T., Lei, K., Zhang, B., & Fang, T. (2021), "Vision-based framework for automatic progress monitoring of precast walls by using surveillance videos during the construction phase", Journal of Computing in Civil Engineering, 35(1), Article 04020056. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000933

Welbourne, E., Balazinska, M., Borriello, G., & Brunette, W. (2007), "Challenges for pervasive RFID-based infrastructures", Fifth Annual IEEE International Conference on Pervasive Computing and Communications Workshops. Advanced online publication. https://doi.org/10.1109/PERCOMW.2007.26

Wong, K. V., & Hernandez, A. (2012), "A review of additive manufacturing", ISRN Mechanical Engineering, 1–10. https://doi.org/10.5402/2012/208760

Yang, J., Vela, P., Teizer, J., & Shi, Z. (2014), "Vision-based tower crane tracking for understanding construction activity," Journal of Computing in Civil Engineering, 28(1), 103–112. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000242

Yang, R. J., Gunarathna, C. L., McDermott, V., Lingard, H., Zhao, H., & Liu, C. (2020), "Opportunities for improving construction health and safety using real-time H&S management innovations: A socio-technical-economic perspective", International Journal of Construction Management, 20(5), 534–554. https://doi.org/10.1080/15623599.2018.1490866

Yankov, P., Petrova, S., & Todorova, S. (2021), "Digital advantages for the construction industry", Izvestia Journal of the Union of Scientists - Varna. Economic Sciences Series, 10(3), 21–32. https://journals.mu-varna.bg/index.php/isuvsin/article/view/8336

Zhang, H., Yan, X., & Li, H. (2018), "Ergonomic posture recognition using 3D view-invariant features from single ordinary camera," Automation in Construction, 94, 1–10. https://doi.org/10.1016/j.autcon.2018.05.033

Zhang, M., Shi, R., & Yang, Z. (2020), "A critical review of vision-based occupational health and safety monitoring of construction site workers", Safety Science, 126, 104658. https://doi.org/10.1016/j.ssci.2020.104658

Zhang, S, Chen, J., Lyu, F., Cheng, N., Shi, W., & Shen, X. (2018), "Vehicular communication networks in the automated driving era", IEEE Communications Magazine, 56(9), 26–32. https://doi.org/10.1109/MCOM.2018.1701171

Zhang, S, Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C. M., & Teizer, J. (2015), "BIM-based fall hazard identification and prevention in construction safety planning", Safety Science, 72, 31–45. https://doi.org/10.1016/j.ssci.2014.08.001

Zhou, W., Whyte, J., & Sacks, R. (2012), "Construction safety and digital design: A review", Automation in Construction, 22, 102–111. https://doi.org/10.1016/j.autcon.2011.07.005

Zhou, Z., Goh, Y. M., & Li, Q. (2015), "Overview and analysis of safety management studies in the construction industry", Safety Science, 72, 337–350. https://doi.org/10.1016/j.ssci.2014.10.006

Zhu, Z., Dutta, A., & Dai, F. (2021), "Exoskeletons for manual material handling: A review and implication for construction applications", Automation in Construction, 122, 103493. https://doi.org/10.1016/j.autcon.2020.103493