Emerging Technologies for Health, Safety and Well-being in Construction Industry

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Abstract New technologies brought about by digital transformation in the construction sector will inevitably lead to a change in the traditional ways of dealing with health and safety risk management as has occurred with other specialties such as architecture, structural, mechanical, electrical, heating and ventilation. Existing procedures will need to be adapted, and new routines are created. The technical and soft skills of employees will need to be updated, enhancing competitiveness and sustainability. Based upon ongoing research studies, this chapter aims to explain how health, safety and well-being (HSW) risk management and associated skills can be dealt with using technologies such as building information modelling, virtual and augmented reality, Internet of Things, teleoperation, soft skills, artificial intelligence applied to big data and cybersecurity. Fields where these key technological developments (KTD) can be applied include: technical training; documental/contractual management; hazards identification; on-site monitoring and implementation; emergency planning; and accident investigation. High-level risks including pedestrian/vehicle collisions and falls from heights will also be covered.

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Based on a review of the relevant literature, an analysis of the application of KTDs to the main fields indicated in EU directive 92/57/CE has been conducted. The main conclusions are that if correctly implemented, these new ways of handling risk management will enable a better perception of risks and enhanced preventive measures, allow improvement of training levels, logistic and financial management and, promote improved integration of prevention measures into work planning. Raising, the skills levels of HSW will be a key enabler for teams to increase their knowledge and understanding of KDT in HSW contexts.

Keywords Health · Safety and well-being · Risks · Building information modelling · Virtual reality · Augmented reality · Internet of Things · Big data · Artificial intelligence · Teleoperation · Soft skills · Cybersecurity

1 Introduction

This chapter covers the influence of Industry 4.0, i.e. the trend towards processes of automation and data exchange utilizing new technologies to support the process, and it's impact on health, safety and well-being (HSW) outcomes in construction, and the new skills needed to ensure successful implementation. The authors have a combined experience in the sector as researchers and/or practitioners covering more than three decades. They have observed at first-hand how HSW processes have developed to increasingly incorporate the adoption of modern technological practices. The pace of change continues to grow ever faster due to improvements in the technologies available, but it has recently accelerated further in the architecture, engineering, construction and operation (AECO) sector as it responds to the challenges presented by the COVID-19 pandemic. Such technologies led to changes that are now commonly referred to as Industry 4.0. Consequently, it is vital that the AECO sector understands how to best implement new processes to leverage their successful adoption within HSW. The following components apply globally to the AECO sector and have been selected as the basis of this analysis, from a review of relevant literature:

(1) **High accident rates**
Accidents occur at high rates despite several improvements in construction processes. Factors influencing this include the increasing complexity of site operations and increasing fragmentation in the subcontracting supply chain. Safety statistics for construction indicates high fatality, injury and illness rates all over the world [1], both in the construction phase and in the maintenance phase, leading to a considerable financial and logistical impact on companies with short, medium and long-term repercussions.

(2) **HSW approach**
Prevention is not always a priority, increasing the risk of accidents at work and occupational diseases. As safety should always be of prime importance,

regardless of deadlines and economic interests, a change of mindset is needed [2].

(3) **New technology adoption**
The AECO sector is experiencing changes influenced by the need to improve the methods employed in undertaking ever more complex projects with increasingly strict budgets, faster pace of construction and higher quality. A seamless integration between the physical and digital world to enhance working capabilities [3] can help to achieve the required improvement. Due to a myriad of terminologies presented for digital technologies through the reviewed literature, this chapter will refer to these as key technological developments (KTD) for reasons of simplification. These collaborative technologies covering design and construction management have become a fundamental response to the growing need for optimization of processes, procedures, decision-making and business models, running through the entire construction project life cycle. However, in the case of HSW management, KTD have not yet achieved the prominence they have in other disciplines related to construction.

(4) **Legal requirements**
The hierarchy of controls indicated in ISO 45,000:2108 [4] gives rise to the urgent need to take into account the latest KTD. This will facilitate timely, easy-to-interpret and sufficiently efficient management measures and expedite the way to integrate HSW priorities into other design considerations.

(5) **Standardization/regulatory reasons**
Innovative technologies need standardization to have a uniform and efficient application [5]. In the case of building information modelling (BIM), this has been mainly driven by 'PAS-1192–6:2018—specification for collaborative sharing and use of structured health and safety information using BIM' [6]. One of the points that PAS 1192:6 indicates is that 'the use of 3D and 4D models in design supports the principles relating to an 'inherently safer design', 'safety by design' and the legislative duties on designers' which is very important as designers' views and approaches to risk are crucial in reducing them. The majority of PAS-1192 series has now been withdrawn and replaced by parts 1, 2, 3 and 5 of the equivalent ISO19,650 suites of standards. However, at the time of writing, there were no plans to create an ISO equivalent of PAS-1192–6:2018 [6] to facilitate continued logical alignment between the BIM-PAS and ISO suite of documentation.

(6) **New skills required**
While industry is reconfiguring working practices, the pace of change in the skills needed is also accelerating, and a lack of skilled individuals will lead to a bottleneck in this process [7]. Therefore, it is essential to identify the required skills and propose a roadmap to upskill the workforce [3]. Note that the UK Government is already seeking to address this through Digital Built Britain whose strategic plan refers to 'training the public sector client in the use of BIM techniques' as one of the key measures. The plan states that the long-term success

of their strategy should be underpinned by an education and change management programme that would assist the industry to develop suitable skills [8].

The intention of this chapter is to analyse the main potential of each KTD for HSW management and the key skills for HSW practitioners. Taking in account the technical-scientific gaps identified in the literature review, three research questions (RQ) were established:

RQ1—What is the main potential of KTD in each HSW priority area?

RQ2—What are the key skills HSW practitioners need in the digital age?

RQ3—What are the main strengths, weaknesses, opportunities and threats influencing KTD implementation?

Answers for these RQ are covered in Sect. 4. Providing construction stakeholders with a list of KTD applicable to improving HSW management along with identifying their key benefits and barriers will facilitate better knowledge and understanding of them. This in turn will encourage increased adoption of KTD solutions, especially amongst smaller contractors who are typically more likely to be resistant to change. In this way, safety performance throughout the industry should be improved [9]. The following section outlines the study context and current technical-scientific gaps. It provides an overview of the status of KTD implementation in HSW management in construction, whilst Sect. 3 presents the approach to the research, and Sect. 4 provides the results, demonstrating the feasibility and effectiveness of the concept. Section 5 covers the conclusions, explores limitations and explains future trends.

2 KTD in HSW Management Systems

2.1 Integrating KTD in HSW

This chapter focuses on the most listed KTD in the literature: building information modelling (BIM), virtual reality (VR), augmented reality (AR), Internet of Things (IoT), teleoperation, artificial intelligence applied to big data (AI/BD) and cybersecurity as applied to HSW.

The correct management of HSW is a critical factor to the success of any construction project and has been widely recognized as one of the most influential aspects in companies' overall performance [10]. HSW management is a process that intends to identify hazards and risks associated to each task, estimates the magnitude of the risks that cannot be prevented, compares these with benchmarks to establish the degree of risk acceptability/tolerability, determines the most suitable mitigation measures to minimize these risks and define processes to monitor and reassesses risks on an ongoing basis. HSW needs to be managed throughout the life cycle of the asset, for three main reasons: (a) for legal requirements, (b) to comply with the hierarchy of controls and (c) reducing the number of accidents and occupational diseases at work.

According to ISO 45,001, the intended outcomes by health and safety management system should be based on internal and external issues of organizations and in the needs and expectations of interested parties. Figure 1 represents a flowchart on the concept of management the process of occupational health and safety covering to ISO 45,001:2018.

A BIM-enabled HSW management process uses visual media as outputs, such as maps or reports. These are more easily understandable by all those involved by summarizing the analysis performed and showing the results of the risk assessment made. This is fundamental for the successful sharing of information. The formal documents that support HSW management are the health and safety plan (HSP) and the technical file (TF). The HSP is produced in the design phase and indicates the risks which could not be minimized during the design phase; it is then further developed in the work phase. The TF is a reference document which can be used to develop HSW preventive measures in the operation and maintenance (O&M) phase. Through these documents, risks are identified and ranked and preventive measures are established.

It is expected that the AECO sector will begin to understand the advantages of implementing KTD to improve HSW outcomes. A review of the literature indicates that the construction industry, especially larger general contractors, is starting to adopt KTD for use in HSW management [9]. It also shows that the lack of automated preventive information is one of the many factors are the basis of the poor performance of HSW management in construction. A number of advantages have

Fig. 1 Flowchart on the concept of management the process of occupational health and safety according to ISO 45001:2018 [4]

been shown to arise from the adoption of KTD for HSW management: more effective sharing of HSW information in a virtual environment and reduced likelihood of losing information; better visualization and interpretation of design; a decrease in the amount of time needed to produce outputs; favourable impacts on schedules and costs; savings in HSW practitioners' time; more focus on greater precision; and more strategic ways to improve safety for everyone in the workplace.

The main advantages for the KDTs covered by the research are:

Building Information Modelling (BIM)—a collaborative and parameterized way of working that has been linked to (a) an improvement in safety conditions through a more effective connection with the productive process [1], (b) a decrease in the accident rates in recent years [11] and (c) savings in overall time and effort [11]. See more details about BIM in the Chapter 'Building Information Modelling and Information Management'.

Virtual Reality (VR) and Augmented Reality (AR)—construction safety is one of the clearest use cases for VR [3]. VR also requires less cognitive load for workers and increases their enthusiasm to learn and improves safety knowledge as well as operation skills [12]. It also enables that training and other activities to be moved to a virtual and safe environment, connecting to remote actors and simplifying complex problems. AR is also being applied to HSW, mainly by simulations in augmented and safe environments, enhancing capabilities of actors. See more details about VR and AR in the Chapter 'From Building Information Modeling to Extended Reality'.

Internet of Things (IoT)—sensor or image-based location systems connected to remote computers using options such as radio frequency identification, Global Position Systems and wireless local area networks can create a large and complex network structure that enables better HSW data capture and sharing over a networked system. IoT enabled new features such as smart personal protective equipment, sensors for hazard alerts, access control linked to training data and maintenance condition monitoring in hazardous environments. See more details about IoT in the Chapter 'Cyber-Physical Construction and Computational Manufacturing'.

Teleoperation and swarm construction—remotely operated systems such as unmanned aerial (or ground) vehicles (UAVs or UGVs) are a great platform to collect data as they can move, in a safer way, faster than humans into hard-to-reach areas of jobsites and can be equipped with devices to transfer real-time data to safety managers replacing expensive, inaccurate and time-consuming manual data collection [13]. Swarmbots, i.e. using several robots in combining to carry out a specific task can also play an important place in this evolution as they can also be deployed in hazardous places without placing operators in risky situations. See more details about remotely operated systems in the Chapter 'Reality Capture: Photography, Videos, Laser Scanning and Drones'.

Artificial Intelligence (AI) applied to Big Data (AI/BD)—HSW data is often too large to analyse and interpret using traditional data processing applications. AI/BD can be used to replicate the way the human biological brain carries out problem solving using computer systems (such as neural networks or genetic algorithms) at an exponential accelerated rate. These systems perform routine tasks that involve grouping and interpreting highly repetitive tasks, large volumes of structured and unstructured data (images, audio files, sensor data, text) and saving HSW practitioners' time. Deep learning and natural language processing can maximize this analysis, enabling AI to solve bigger problems more efficiently as well as generate predictions and suggestions for preventive actions that HSW managers can quickly act on [14]. See more details about AI/BD in the Chapters 'Artificial Intelligence for the Built Environment' and 'Big Data and Cloud Computing for the Built Environment'.

Cybersecurity—where KDT are employed as part of Industry 4.0, cybersecurity is an essential part of the landscape and is required to protect systems, assets and people and their corresponding data and privacy.

The increasing trend towards real-time monitoring and control of projects and assets through their full lifecycle provides an opportunity for malicious individuals and organizations to disrupt normal operation. There is more collaboration and sharing of sensitive data about individuals, the asset's condition and its operation. Standards, such as ISO19650 Part 5 [16], have been developed in response to this, advocating a security minded approach to manage the associated risks. It seeks to protect hardware, software, and data from malicious threats (e.g. hackers), cyber terrorists and/or industrial espionage [14] and can be used to protect HSW systems (and people depending on them) from those threats. Construction sites can be particularly vulnerable due to the high numbers of employees from different organizations moving on and off the project but still requiring access to sites and digital systems. See more details about cybersecurity in the Chapter 'Blockchain Opportunities and Issues in the Built Environment: Perspectives on Trust, Transparency and Cybersecurity'.

All these KTDs are different but complementary to each other and can be used in an integrated way to enhance workers' real-time communication ability in an ever-changing environment. These KTDs still have low uptake in most AECO organizations although there are already some cases where KTDs have been successfully implemented [15]. There is, therefore, a clear need for researchers to focus more on technology transfer from research into practice to support the entire process of construction site safety management. It must be stressed that KTD implementation will depend on worker/user acceptance if they are to be successfully deployed over time. KTDs have the capability to greatly improve performance and can minimize human interaction, but they are not well-equipped to identify human emotions and react accordingly.

2.2 Skills

The future of work is amongst one of the most largely debated topics around the world due to exponential discoveries in the technology domain. Poor productivity and skills shortages are leading to high construction costs, delays in construction projects and poor sustainable practices in the construction sector which makes skills an important factor when studying the implementation of KTD. There is a wide agreement that the advancement of automation and digitalization will continue to transform the skill requirements for employees over the coming years and that the need for competent workers is central for successful safety and health technology adoption and implementation [9]. The recent EU 2030 high-tech skills report highlights new and innovative skills for the construction professionals, which are in line with the paradigm of smart industrial specialization and digital transformation [7]. The intersection of soft and technical skills is still a challenge requiring different approaches in training practices and life-long learning, as reskilling to keep up with technology is an important part of maintaining a valuable workforce of all ages [7]. This will require additional effort from employers and individuals in order to achieve upskilling if they are to be capable of responding as rapidly as possible to changes in skills requirements triggered by digitalization [16]. Therefore, KTDs inevitably imply a need for the skills of HSW practitioners to be upgraded.

Since, a qualified workforce is a crucial factor for the successful adoption of KTD such as AR and VR [3]. As a response to these challenges, the combination of technical and non-technical skills is expected to be in high demand. The next sections will discuss how different KTDs could be used for HSW management.

3 Approach to Research

For the first research question (What is the main potential of KTD in each HSW priority area?), the approach used, as starting point, was the Council Directive 92/57/EEC on the implementation of minimum safety and health requirements at temporary construction sites. Following an analysis of the directive, its requirements were grouped and KTD applicability was analysed for each one. Six groups were created: (1) documental/contractual management; (2) hazards and risk identification; (3) training; (4) on-site monitoring and implementation; (5) emergency planning; and (6) accident investigations. Based on the literature review, the authors then evaluated the level of appliance of KTD for each area individually and the results used to form a consensus view. Three levels of applicability for each KDT were established: low (L), medium (M) and high (H) as presented in Table 1.

For the second research question (What are the key skills HSW practitioners need in the digital age?), a list of key skills was compiled based on the literature review. For the third research question (What are the main strengths, weaknesses, opportunities and threats influencing KDT implementation?), a SWOT analysis was carried out to analyse the strengths, weaknesses, opportunitie, and threats applicable to KDT implementation in HSW planning.

The barriers that prevent organizations or individuals from adopting a technology need to be addressed as part of HSW strategy development. The SWOT analysis is included in Sect. 4.3.

Table 1 Level of applicability of KTD versus each area/group

Fields	BIM	VR	AR	IoT	Teleoperation/ swarm	AI/ BD	Cybersecurity
Contractual/documental management	H	L	L	L	L	M	H
Hazard and risk identification	H	H	H	H	M	H	M
Training	H	H	H	M	M	L	L
On-site monitoring and implementation	H	M	M	M	M	M	H
Emergency planning	H	H	H	L	L	M	M
Accidents investigation	H	M	M	L	L	M	M

4 Results and Discussion

4.1 Document and Contract Management

The growing complexity of construction projects necessitates an increase in the requirement for better contracts and more collaboration between stakeholders as increased requirements usually imply greater volumes of documentation to effectively document the tasks and processes. Current HSW systems can prove to be unsuitable, and this translates into excessive numbers of large, unstructured and difficult to understand procedures [17]. These may be considered tedious by those who need to implement them and therefore are often not integrated into work planning which limits the possibility to identify and analyse dangers before the beginning of the construction phase [1]. Additionally, sources used by HSW managers (such as paper, speech or images) contain hundreds of attributes, often lack structure and are time-consuming to capture, analyse, combine and interpret. This can hinder the interpretation of relevant information. KTDs provide essential tools to set the contractual framework for the design, construction and O&M phases and to organize the usually high amount of data that may need to be made available during the tender phases. The use of BIM common data environment (CDE) provides a standard compliant environment to specify, collect, assure, store, present and manage BIM information (structured data documents and 3D models) in a collaborative spirit [18]. A CDE also enables all project participants to access information from any communication device with Internet access. Due to the large amounts of data that have to be managed during the life cycle of major infrastructure, AI applied to BD appears to be valuable KTD that can be used to gather, systematize, analyse, interpret and carry out content analysis automatically using the right data from all data-generating devices or agents (e.g. HSW data provided by sensors). This way, AI/BD can tackle complicated and nonlinear practical problems and once trained could undertake predictions and generalizations at high speed. This could cover the analysis of historical BD (e.g. site conditions) to identify patterns and probabilities of construction risks for performance improvements in future projects or enhanced decision-making [19]. Another way of benefiting from KTD in contractual arrangements is by setting requirements for the designers or contractors, e.g. by the BIM's exchange information requirements (EIR) [20]. These are the clients' specification for what, when, how and for whom information in connection with the appointment (of a designer or contractor) is to be produced as identified in the information protocol and/or provided in accordance with the information standard' [20]. The designers and construction companies then prepare and present the BIM execution plan (BEP), as a response to the demands in the EIR. This information exchange, divided into the EIR and the HSP/TF, is of paramount importance for correctly understanding the project owner's intentions regarding the construction and O&M phases of the built asset. The use of KTD can also be used to improve cost management. BIM systems can carry out automatic and early measurement of HSW equipment which reduces the time to prepare cost estimates per activity and budgets with increased the accuracy of results. This, in turn, can reduce the potential for future financial disputes. With automated quantity extraction (which is not possible to do with the traditional process), it is possible to easily obtain a list of preventive elements (such as guardrails, barriers or signs) to be installed or assembled at any given time. This is especially useful in dealing with many changes to the construction site structure or work planning. Simply adding the unit costs to this list produces a complete budget [21]. It also becomes possible, at any phase of the work, to know what material is required, as well as the estimated final cost related to the construction site assembly and maintenance activities and the staggered cost of each portion. This information can be used to optimize the financial management of suppliers, in terms of current operation, changes in materials, equipment and workforce that occur and for budget forecasts [21]. Cybersecurity good practices need to be applied where the electronic exchange of data is involved, particularly with sensitive data, and data about individuals. This information covering individuals, the built asset and associated cyber-physical systems needs to be protected as recommended by ISO19,650–5:2020 [22].

4.2 Hazards and Risks Identification

The usual HSW approach to identifying hazards and risk is usually verbal based on personal experience and the use of two-dimensional drawings. The results obtained are often prone to error due to subjective assessments [21]. In reality, with the exception of larger projects, the quality of the health and safety plans and the health and safety file is often far below what would be desirable, and it is necessary to create mechanisms to fill the gaps identified and reduce risks to acceptable levels. In addition, HSW is generally viewed as separate from planning, and this perspective makes it difficult to analyse which preventive measures are needed and when and where they will need to be implemented. Failing to identify safety hazards is a major cause of accidents as it is almost impossible to identify all hazards before the start of construction.

The ability to identify hazardous conditions before starting a task is a valuable tool to promote proactive HSW management and decrease associated costs. Specific fields where KTD can be used for risk management and their advantages are as follows:

BIM: enabling the representation of risks [6] in design phase improves the capacity of actors to improve timely risk identification [21] and mitigation [6] and minimizes risks before the onset of problems on the ground. This enables minimization of errors resulting in time and cost savings. It provides better identification of areas or times when there is a higher level of risk. It makes it easier to identify potential constraints, both in the workspace and in the surroundings [21]. BIM also provides the opportunity for early and more structured approaches to the testing of several HSW solutions (e.g. in construction site assembly as shown in Fig. 2) allowing temporal and financial scenarios and hazards to be forecasted in advance. It also improves task-planning capacity [21], as well as resources allocation planning for each task [23], reducing the number of possible uncertainties about the project and minimizing the need for improvisation or last-minute solutions [12]. The identification of preventive measures can be carried out in a more automated way [11]. Any change made for reasons related to the production area of work implies a change in preventive terms, which is quite simple to make automatically [21].

BIM rule-checkers are a very useful tool for risk identification as they perform automatic checking by comparing reality to safety rules databases. The latter must include data about all risks, known previous accidents, and relevant preventive

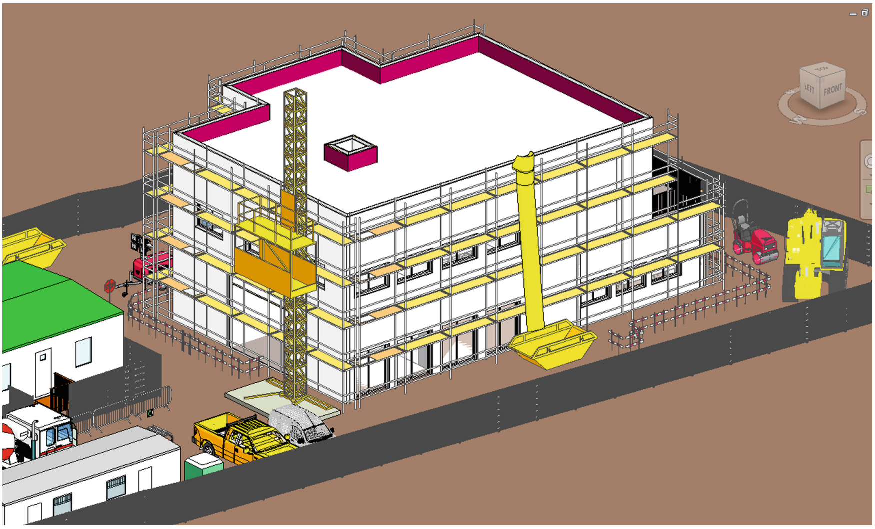

Fig. 2 Typical construction site through a BIM perspective [21]

measures. For example BIM and safety rules can be applied to visualize the scaffolding installation process and identify associated potential hazards [24], while safety protection can be automatically provided through the analysis of the time and place of the installation and removal of guardrails and scaffolding.

VR and AR: there are many examples where VR and AR have been used to help with in hazard and risk identification through simulation of virtual scenarios. Evidence from previous studies has shown that most users in the virtual environment assessed higher risk levels and identified more hazards than those who studied photographs and documents. The use of augmented risk information allows the managers and workers to quickly identify the exact risks and their location on a construction site, which means that the time allocated to supervision could be decreased. VR can also be applied to site planning, simulating the layout of construction site facilities and allowing users to create their own site layout environment. They can manually select and place objects representing the site facility and equipment. This is then used to create a walk-through view of the virtual facility. The visualization provided by AR and VR simulations can be used to provide predictive and prescriptive analysis leading to better and more efficient decision-making [3]. Robotics and sensors will probably also have an important paper as they enable to risks detection, e.g. in human non-accessible zones.

AI/BD: artificial intelligence is likely to play an important role in HSW area, having the capacity of predicting occupational hazards, using the data obtained from automatic identification and storage of previous records of unsafe behaviour as a source. Analysis of worker violation data can indicate the most dangerous time, the most dangerous area or even the most risk-seeking worker. This feature will enable better and more efficient decision-making [3].

4.3 Training

When it comes to safety training, several countries have adopted systems, both in classroom and field [25], to ensure a minimum level of training through lectures, videos or demonstrations. These traditional training methods often fail to achieve the desired goals due to their significant pedagogical limitations including: (1) indoor static classroom presentations with no hands-on training elements often fail to engage with the workers which can lead to a lack of interest, impeding the retention and retrieval of critical safety concepts [26]; (2) video-based guides have a high degree of realism, but once they are developed, they cannot be easily modified, and they do not always show a practitioner sufficient detail for a given step or process; (3) due to their passive nature, they do not necessarily allow a practitioner to test their understanding, so they must wait until they physically try to perform what they have been taught before they know if they understood the material [27]; (4) the complexities and spatial characteristics of the specific construction site are not properly represented; (5) the transient and temporary nature of the workforce hinder the implementation of different KTDs as not all employees are at the same skill levels; (6) there may be a lack of knowledge transfer due to workers not being taught in their native language or have low literacy levels and not properly understanding the training message; (7) schedule-intensive projects have time constraints due to on-site training interfering with normal construction activities which reduces productivity.

Using KTD for training allows users to easily and repeatedly experience different and unlimited scenarios that were previously impossible, dangerous, hard or expensive to replicate. From this, they can more easily identify possible problems. KDTs also have the potential to provide a means of rapidly conveying information, namely to those who tend to be less able to interpret drawings. BIM corresponds to a faster way to share information [23], improving communication between all actors; with outputs easily used for training purposes [11], this minimizes or eliminates the typical gaps in communication [21]. VR is expected to reduce the required level of language proficiency and literacy and increase the understanding of those in construction who lacks fluency in English removing any language barrier [1].

Using virtual environments, through glasses, gloves or headsets, reduces the time it takes for a learner to become competent and operational in their field of work, and they produce memorable and lasting experiences for trainees [28]. AR is the ideal technology to display hazard information as it enables workers to improve identification of field safety risks, it improves risk recognition [29] and enhances real-time communication between the construction manager and workers. A significantly growing trend is the use of 3D game engines for the gamification of training. Recent studies shown the potential benefits of using 3D game engines: allows users to perform construction operations within a virtual environment; actors face challenges that make sense in real-life situations; can include of avatars as pedagogical agents [27]; maintain a low-cost development and execution platform; can drive higher learning by allowing higher rates of completion, learning and retention [27]; using multiple player options can increase participant engagement making the employees understanding greater and more lasting.

4.4 On-site Monitoring and Implementation

Site monitoring is key to safety management and depends on the number of HSW staff available for the task. It is usually based on using checklists which are neither sufficiently timely nor accurate enough to successfully manage construction HSW through the identification and recording violations. In the absence of technological support, it is impractical to monitor the whole site simultaneously due to its large size and dynamic environment. However, the lack of periodic HSW inspections can increase the rate of accidents. KTDs have the potential to significantly improve the ability to identify and track people and objects (workers or equipment) in a quick and understandable manner [3], using either UAV's or UGV's equipped with cameras or sensors. The latter can be three axial (sensors or accelerometers) embedded in physical objects, such as heavy equipment, robotics, building components or personal protective equipment with the ability to connect to the Internet in real time, by Bluetooth, radio frequency identification (RFID), ultra wide band (UWB), wireless sensor monitoring (WSN), QR codes and Global Positing System (GPS). Capturing data on the progress of construction projects, worker activities, vehicle activities, weather conditions and conditions on-site in data warehouses will then provide the information needed to drive data analytics and artificial intelligence algorithms [30]. Monitoring equipment location is also imperative, as safety conditions can be compromised by unfavourable factors such as lack of training, blind zones of heavy vehicles or even sudden changes in weather conditions [3]. These conditions may lead to accidents, e.g. vehicle impact or a crush injury. AR will also be fundamental as it enables, by augmenting information in real environment, to know what kind of HSW component should be placed in each zone.

KTD tools, such as portable tablets capable of retrieving applicable safety procedures, rules and regulations and software capable of automating recurring activities (e.g. creation of violation statistics and reports), can significantly improve the day-to-day practices and management of safety inspections [31].

KTD can be used to monitor site conditions as follows:

Environmental conditions—levels of noise, heat, radiation, vibration, humidity, air quality, wind, condition of power tools and heavy on-site equipment, structural conditions of scaffolding and other supportive structures can be monitored with results being storage, in real time, in central systems.

Workers and equipment—identifying which workers are on a construction site [19]; alerts as to the proximity of dangerous equipment or entry into unauthorized areas such as safety perimeters, unprotected edges or openings; collecting trajectory data for investigating worker's risk behaviour-based trajectory prediction models or automated trajectory and path planning [32]. Another use of KTD is to detect and identify workers posture, e.g. body rotation/orientation, and actual physiological vital signs, such as blood oxygen or heart rate so that the earliest signs of safety issues arising from health problems or accidents can be detected and corrected [39]. KTD can also be used for the analysis the use of PPE to ensure that all workers are correctly equipped with the correct and required PPE using AR tools [32]. This can be done by combining video analysis, algorithms and machine learning, matching what a worker is wearing (headgear, eyewear, footwear or other required PPE) against pre-set rules for entering a work area. Non-compliance could then be detected, restricting access until solved. These kinds of checks are, of course, nothing new, but they are typically conducted by a person and, therefore, prone to human error.

Activities in progress—KTD can be used to monitor site activities in real time. One good example is the use of UAV/UGV that can improve risk detection such as potential electrocution accidents due to contact of boom vehicles and cranes in the proximity of overhead power lines, detecting potential fall hazards due to improper use of fall protection systems or working near unprotected edges or openings [33]. All this information about environment conditions, workers/equipment and activities in course that can be remotely done reducing the frequency of the inspections on site, can be uploaded and managed through a BIM model.

Teleoperation/swarm construction—KTD can provide safer solutions in terms of dangerous work. This involves, using drone or robots, solution that offers clear safety advantages when compared to physical operation on-site, in hazardous and harmful environments, as operators have reduced exposure to risks. In order to increase HSW performance, drones and robots can undertake dangerous and demanding tasks, which persons prefer to avoid or are unable to carry out due to hazards and particularly extreme conditions. Current applications of teleoperation include handling in dangerous conditions (e.g. extreme hot) or extreme environments (e.g. environments with dangerous gases) and demolition tasks [3].

Support devices such as exoskeletons: since musculoskeletal disorders are one of the actual concerns of HSW practitioners, exoskeleton offers a new approach as they actively support the muscle-skeletal system using mechanical principles to aid workers, e.g. carrying heavy tool kits [30]. This offers great potential to improve for the health of workers as it is assumed that muscle fatigue increases the risk of injury [34].

Cybersecurity will help to guarantee that wireless transmissions are not hacked into, as that could endanger all the connected people and systems also known as cyber-physical systems. A security-minded approach is needed to assess vulnerabilities and implement mitigating strategies [22], keeping people and systems safe from malicious attacks.

4.5 Emergency Planning

The first step to minimize risk due to emergencies is to set up a contingency plan for each scenario [35]. This plan should cover the possible disaster or accident scenario, first aid, rescue, and evacuation operations and the maintenance of the minimum power supply for operation of vital infrastructures, which should be done in cooperation with external support bodies. KTD can be used as BIM improves emergency planning, namely regarding evacuation routes and safe emergency-response procedures; VR is able to provide more precise disaster scenarios and post-action evaluations, e.g. to simulate indoor evacuation under fire emergency conditions [3], identification of the shortest escape routes using AR and VR [3].

4.6 Accident Investigation

Accidents at work have a huge impact in companies due to their effect on production, logistics and finances. Even though this is a negative indicator [36], knowing the conditions in which an accident occurred or an occupational disease appeared has the following advantages: (1) provides an important foundation to monitor and prioritize preventive measures; (2) decreases the probability of making wrong decisions; (3) helps companies to fulfil their legal requirements regarding risk assessment and to make better decisions that minimize their costs [37]; and (4) it allows learning from past mistakes. KTD can be used to deal with accidents and diseases in several ways: BIM improves the capacity to analyse accidents at work [11] by recreating the sequence of events that lead to the accident and illustrate the flaws found; VR can help simulating conditions of accidents and near-misses [3] or fire/explosion accidents in a virtual space [28]; sensors in personal protective equipment could help recognize all cases where people slipped or stumbled; robots can access disaster sites [3]; and AI/BD can automatically extract, at low or no cost, attributes (e.g. incident type or body part affected) from injury reports, and this could predict the outcomes.

4.7 Skills

Table 2 systematizes the authors' opinion regarding the key skills HSW practitioners need to have to be effective in their tasks. The skills identified are supplementary to those that are mandated by legislation.

4.8 SWOT Analysis

With the objective of understanding framework for implementing KTD for HSW purposes, authors performed a SWOT analysis that is based in their previous experience. This topic is divided in four different fields: strengths, weaknesses, opportunities and threats.

Strengths can be listed as follows:

- Ease of implementation if KTD are already being used in house.
- New solutions to old problems.
- Simplification of information gathering and optimization of information flows.
- Potential risks are hard to identify using 2D drawings.
- Potential to be used in several areas of HSW.
- Productivity improvement due to faster information exchange and overall cost reduction.
- HSP and TF managements efficiency improvement.
- Integration of safety into the productive process and saving administrative resources.

Weaknesses can be listed as follows:

- Resistance to changing the traditional process;
- Associated cost and time linked to training.

Table 2 Skills needed for HSW through KTD

Theme	Skills
General skills	English as a foreign language for training foreign workers
	Solving hardware/software basic problems and conflicts
Specific KTD knowledge and skills	Understand copyrights and licences
	Know the general/specific concepts and application of each KTD
	Work with remote teams in specific tools (CDE)
	Edit/create, through 3D/4D tools and plug-ins, activities planning
	Know the potentialities of simulators for training
	Principles about data security and vulnerabilities
Physical skills	Body coordination and flexibility (arm-hand- finger steadiness/dexterity)
Socio-emotional	Feeling physically safe, secure and healthy
	Openness to learn and interact with KTD in workplaces
	Active learning, flexibility and adaptability to KTD procedures
	Good interpersonal/intercultural/collaborative relationships
	Time management
	Innovative thinking and creativity
	Emotional intelligence—understanding someone's online emotions
	Critical thinking and analysing online arguments
	Conflict management in dilemma safety/production
	Social intelligence—perceptiveness, persuasion and negotiation

– Poor KTD knowledge/investment by SME's.
– Time taken to become familiar with equipment.
– Changes to procedures and responsibilities.
– Lack of free trial of software.
– Integration of different KTD.
– Time and cost of creating models with safety data.
– Some devices are too fragile and not suitable for environmentally complex construction sites.
– Lack of interoperability affects real-time changes.
– Poor internet connectivity on construction sites.
– User interfaces are sometimes poor.
– Screen visualization can be difficult in some site environments (foggy or rainy).
– Short battery life of devices.
– Virtual experiences are difficult to record.
– HSW regulation compliance may be difficult.
– Interference with normal construction activity.

- Changes difficult to import into the BIM model.
- Security and privacy issues.

Opportunities can be listed as follows:

- Models can be used in future.
- Easier access to information.
- New solutions to old problems.
- Potential to lower accident rates.
- Differentiation tool in terms of competition.
- Quantifying costs.
- Change of focus in the HSP and TF managements.
- Improves the decision-making process.
- Purpose-built training facilities that physically simulate the construction site.

Threats can be listed as follows:

- Lack of political and corporate will.
- Standards and regulations not developed.
- Customer relationship changes.
- KTD requirements not part of the contract.
- Stakeholders not familiar with KTD.
- Difficulties in developing the team's skills.
- Time to get familiar with the new procedures.
- Changes in work practices affect productivity.
- Reluctance to share information.
- Replication may be difficult as projects are unique.
- Staff who fail to adapt may feel threatened.
- Reliance on workers who understand KTD.
- Maintaining data during construction.
- Limited technical support from suppliers.
- KTD may increase safety, but they also reduce efficiency if poorly implemented.

5 Conclusions

There has been a broad increase in the understanding and application of KTD in real cases of design, construction and facilities management over the past few years. There are already some companies, mainly large organizations, investing substantial efforts to implement KTD for HSW purposes in real scenarios despite some like VR and AR still being relatively immature. However, SMEs are likely to experience significant difficulties in the procurement, implementation and application of KTD for several reasons including cost, time and availability of resources.

Evidence to support the effectiveness of all KTD for HSW management must be reinforced and return on investment of each KTD in each individual case must be calculated as there is no 'one size fits all' approach. Applying KTD to HSW management proves very promising and has some positive impacts on optimization of times and costs (two very important aspects for the financial management of companies), with an increased production efficiency and a better connection between production and HSW. This approach can lead to a paradigm shift with greater potential to prevent work accidents and incidents; due to its influence on risk identification and preventive measures implementation, regarding communication, training, implementation and inspection aspects. Implementing KTD in companies requires a collaborative culture; people need to have adequate skills and be trained in the importance and usefulness of the technology, and that HSW managers have acquired suitable skills related to these KTDs. The transposition of HSW documents into a KTD format proves to be a task that requires the efforts of all stakeholders, especially in scenarios characterized by a multidisciplinary nature of the work teams and of multi-organizational scope. It is also noted that this approach has the potential to streamline the HSP and TF analysis and validation procedure, in accordance with current legislation. Several factors such as social, legal, financial and behavioural, that may change over the years, will affect KTDs implementation in the HSW area. It is difficult to make predictions about which applications will have a higher level of development or impact in the coming years. By enabling the desired reduction of accident rates, the needs of today's generations could be met without compromising the ability of future generations to meet their own aspirations, which is one of the principles of sustainability. Smart spaces are a next step, but smart spaces must also be safer places. In terms of cyber security, HSW professionals need to be able to understand the vulnerabilities inherent in the various KTD and understand the risks involved by dialogue with experts who will assist in providing solutions to minimize that risk. They will need to understand how the mitigation can be implemented and then monitored to ensure its effectiveness over time. This is where standards, best practice advice and protocols can assist. A key limitation of KTD is that they cover a wide range of technologies, so each KTD discussed here would justify its own chapter.

Future studies should focus on: (1) relative impact of KTD for each group/area identified in Table 1; (2) assessment of which skills are more important; (3) introduction of KTD at an earlier education stages; (4) how to create new purpose-built training facilities for simplifying the logistics required for KTD training; (5) there should be a focus on detecting weaknesses and threats, in order to try and find solutions for them; and (6) cybersecurity should be enhanced in order to avoid threats to workers health, safety and well-being.

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