

Investigating the impact of emerging technologies on construction safety performance

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Abstract

Purpose – Construction safety is heavily affected by using new technologies in this growing trend of technology adoption. Especially, safety performance is enhanced through the utilization of some effective technologies such as artificial intelligence, virtual reality, BIM and wearable devices. Therefore, the main purpose of this study is to investigate the influence of emerging technologies on construction safety performance and quantify the relationship between those. The proposed components of emerging technologies are BIM, GIS, VR, RFID, AI, ML, eye tracking and serious games and wearable devices, whereas the dimensions of construction safety performance are safety planning, safety training, safety inspection and monitoring, safety audits and reviews and safety leadership.

Design/methodology/approach – A structural model was composed consisting of emerging technologies and safety performance indicators. Then, a questionnaire was designed and administered to construction professionals, and data from 167 projects were analyzed using structural equation modeling. The data were analyzed by using software, called SPSS AMOS.

Findings – The analysis of the structural model proves that there is a positive and significant relationship between emerging technologies and construction safety performance. Moreover, the factor loadings for each factor were found to be high indicating a good representation of the construct by the components developed. Among the technologies, BIM, robotics and automation, AI and wearable devices were detected to be the most significant technologies in terms of impacting safety performance.

Originality/value – The study contributes to the body of knowledge in that it develops a conceptual framework consisting of specific technologies in terms of emerging technologies, reveals the impact of such technologies on safety performance and proposes several tools and strategies for enabling effective safety management along the project lifecycle. Industry practitioners may benefit from the framework developed by adopting such technologies to enhance their safety performance on construction projects.

Keywords Emerging technologies, Safety, Construction industry, Safety performance

Paper type Research paper



Introduction

The construction industry is among the risky sectors due to the occupational accidents that occur frequently due to the dynamic and complex nature of construction projects (CPWR, 2018; Demirkessen and Arditi, 2015; Tezel *et al.*, 2021; Toscano *et al.*, 1996). For this reason, safety is considered a global issue in the construction industry (Zhou *et al.*, 2012). Construction safety has traditionally been dependent on regular safety inspections and the ability of workers to recognize hazards. The complex structure of the construction industry and the difficulties in establishing standardization cause the hazard recognition rate of this traditional management to decrease. Therefore, it is crucial to establish safety management

using technologies based on big data for the construction industry (Wang *et al.*, 2021). The construction industry is one of the least digitized industries when compared to other industries. This situation makes it difficult to solve the problems experienced by the sector (Abioye *et al.*, 2021). On the other hand, emerging technologies are important contributors to construction safety (Oesterreich and Teuteberg, 2016). Therefore, the construction industry can benefit from such technologies to a great extent in terms of improving safety performance. This brings the need for a better analysis between these technologies and construction safety since using these technologies can result in the prevention of work-related hazards and accidents.

To better understand emerging technologies and observe their impact on construction safety, this research proposes a model investigating the impact of emerging technologies on construction safety performance. Despite some studies, this relationship has not been thoroughly assessed yet. In this respect, this study proposes a set of components as part of emerging technologies and aims to measure their impact on construction safety performance through a structural equation model (SEM). The study tests the model with the analysis of moment structures (AMOS) tool of SPSS software.

Research background

Construction is one of the sectors, where there is a heavy discussion about the use of smart technologies for a better safety levels (Forcina and Falcone, 2021). The implementation of new technologies in construction safety is still limited despite the growing interest of researchers and technological developments (Karakhan and Alsaffar, 2019). Research shows that the use of technology in the construction industry has great potential, but it is still used at a low-level (Štefanič and Stankovski, 2019). Since construction industry workers experience long-term risks, they are less susceptible to hazards than workers in other industries (Wang *et al.*, 2017). This causes to low level of awareness of construction safety.

According to the study by Yap *et al.* (2022), it is necessary to switch to a high-tech and professional construction industry to have a better economic environment in developing countries. Nnaji and Karakhan (2020) investigated the use of technology for safety and health management in the construction industry. They mentioned building information modeling (BIM), wearable sensing devices (WSDs), mobile devices onsite (MDO), radio frequency identification (RFID), laser scanning and light detection and ranging (LiDAR) technologies are mostly implemented technologies in the construction industry as of today. In addition, according to this study, robotics and automation, augmented reality (AR), virtual reality (VR), artificial intelligence (AI), camera network systems are the technologies that are expected to be primarily implemented in the future (Nnaji and Karakhan, 2020). Chen *et al.* (2021) highlighted that the most researched technologies for construction safety management in the literature are RFID, immersive media (IM), AR/VR/Gaming and BIM. On the other hand, Zhou *et al.* (2013) listed VR, sensors, databases, 3D and 4D visualization technologies and robotics as the most cited technologies in the literature. According to Okpala *et al.* (2020), BIM, AI and unmanned aerial vehicles (UAV) are technologies that are expected to be used frequently throughout the project lifecycle.

AI is expressed as a field of science that aims to perform tasks to be performed by human intelligence by computers (Chakravarthy, 2019). Machine learning, knowledge-based systems, robotics, optimization, etc. technologies are sub-fields of artificial intelligence. These areas have been successfully applied in many industries for profitability, efficiency and safety purposes (Abioye *et al.*, 2021). AI is an emerging technology in the construction industry (Irani and Kamal, 2014), but it has lagged behind other industries (Štefanič and Stankovski, 2019). AI can make construction safer and automate the decision-making process

regarding safety and risk assessment in construction projects (Bigham *et al.*, 2018; Chakravarthy, 2019). For example, emerging AI technologies can be an important information tool that minimizes risks with a warning message or monitors and prevents risks with visual processing algorithms (Chakravarthy, 2019). Ma *et al.* (2016) created an artificial intelligence-based early warning system to protect workers at high humidity and temperature at construction sites against occupational heat stress. According to Štefanič and Stankovski (2019), individual risk calculations can also be created by including employee health data and exposure times in this artificial intelligence-based system (Štefanič and Stankovski, 2019). Ayhan and Tokdemir (2019) developed an artificial intelligence-based prediction model to predict accidents at construction sites and proved that this model produces good results in predicting serious events such as death.

Chen *et al.* (2021) implied that the most widely used technology between years 2001 and 2020 is BIM. BIM is an information resource that provides opportunities to add, remove, update or modify information to the building model throughout its lifecycle (WBDG, 2021). Studies show that BIM improves construction safety (Alomari *et al.*, 2017; Cortés-Pérez *et al.*, 2020; Enshassi *et al.*, 2016). In addition, there are studies in which BIM is used together with other emerging technologies (Asadzadeh *et al.*, 2020; Mzyece *et al.*, 2019; Yuan *et al.*, 2019).

VR/AR technologies are used in the fields of planning, training and supervision in construction safety (Park and Kim, 2013). VR offers an effective learning platform (Shamsudin and Majid, 2019). Also, VR has great potential for construction workers to protect their safety information (Bhoir and Esmaeili, 2015). Virtual reality can encourage participants' natural behavioral responses by simulating real situations and providing a good grasp of fidelity (Gao *et al.*, 2022). Gao *et al.* (2022), in their study, determined that virtual reality is promising for measuring the safety behavior of construction workers. Le *et al.* (2015a) proposed experiential construction safety training based on social and collaborative VR. Park and Kim (2013) proposed a new safety management system by integrating AR, BIM and location tracking technologies.

Placencio-Hidalgo *et al.* (2022) researched the use of AR in virtual education in the construction industry and determined that this technology is appropriate for the prevention of disability. Kim *et al.* (2019) have shown that AR-based assessment can be a very effective assessment tool that performs well in construction safety training. According to Chen *et al.* (2014), AR can train workers without being exposed directly to hazards and make them less afraid of these hazards. Talmaki *et al.* (2010) created an AR-based visual information model that integrated geospatial data for urban excavation operations. Zhou *et al.* (2017) developed an AR-based safety system for displacement control in tunnel construction.

Pradhananga *et al.* (2021) and Ojha *et al.* (2022) identified the barriers to adopting robot technology in the US construction industry and offered various solutions for improvement. According to Balasubramanian *et al.* (2021), a drone with a camera can eliminate safety risks when climbing tall buildings. For construction safety management, it is of great importance to know the risk perceived by the workers (Lee *et al.*, 2021). Lee *et al.* (2021) designed a wearable wristband using a machine learning approach to identify risks perceived by construction workers. Guo *et al.* (2017) conducted an experiment examining the psychological states of construction workers working at height using smartwatches. This study showed a relationship between the psychological and physical conditions of workers. According to Nnaji *et al.* (2021), the most commonly used wearable devices in the construction industry are smartphone-based devices and smart helmets.

Wearable AR, information processing and visualization, which provide information flow between the project program and applications without intervening in the field environment, are among the topics that will attract the attention of researchers in the future (Chi *et al.*, 2013). Wearable sensors allow timely and accurate physical data to be collected

without interfering with the work of construction workers (Essa, 2000). The use of wearable electroencephalograms gives successful results in determining the construction hazards and the attention levels of the workers (Jeon and Cai, 2021; Wang *et al.*, 2017). Wearable Internet of things (WIoT) is known as wearable devices with sensing, communication and computing features. Despite its widespread use in many industries, the use of this technology in construction safety is limited. However, there is an urgent need to determine the WIoT devices to be used to increase safety at construction sites (Sulbaran and Awolusi, 2022).

According to Bansal (2011), GIS will be appropriate in determining environmental and topographic conditions that cannot be determined by BIM or 4D modeling in safety plans. Manase *et al.* (2011) conducted a study using the geographic information system (GIS) approach to reduce various construction accidents. They concluded that GIS is an effective technique to avoid construction accidents.

An important portion of previous research focused on eye tracking technology in construction safety. Some major areas that were researched are hazard recognition, risk identification, accident prevention and education (Jeelani *et al.*, 2019; Xu *et al.*, 2019; Czarnocka *et al.*, 2020; Park *et al.*, 2022; Hasanzadeh *et al.*, 2017a, 2018). These studies show the effectiveness and importance of cognitive processes in construction safety. According to Hasanzadeh *et al.* (2018), eye tracking is an accurate technique used to measure the attention of workers. Czarnocka *et al.* (2020) implied that visual concentration plays an essential role in predicting the unsafe work chain.

Laser scanning and LiDAR technologies were further assessed in the previous studies. Several research studies mentioned that the use of laser scanning and LiDAR technologies for blind spot detection gives successful results in preventing collision accidents at construction sites (Marks *et al.*, 2013; Ray and Teizer, 2013; Teizer *et al.*, 2010). For example, Kim *et al.* (2022) developed a robot dog scanning system to reduce scaffold-related deaths.

To be able to assess the impact of emerging technologies, it is necessary to identify the factors involved in safety management to improve safety performance (Khalid *et al.*, 2021). One of the most prominent variables affecting safety performance is listed as safety leadership (Khalid *et al.*, 2021; Moosa and Oriet, 2022; Skeepers and Mbohwa, 2015). In addition, safety training was mentioned as another important variable in safety performance (Abas *et al.*, 2021; Chellappa *et al.*, 2019; Moosa and Oriet, 2022; Shaikh *et al.*, 2020; Skeepers and Mbohwa, 2015). Safety planning was another most cited parameter in safety performance (Chellappa *et al.*, 2019; Khalid *et al.*, 2021). Safety inspection and monitoring (Abas *et al.*, 2021; Chellappa *et al.*, 2019; Khalid *et al.*, 2021; Moosa and Oriet, 2022) and safety auditing and review (Moosa and Oriet, 2022; Shaikh *et al.*, 2020) are also directly related to safety performance.

Given this background, this study develops a set of the most trending and implemented technologies in construction projects. Then, a conceptual framework was developed to evaluate the impact of such technologies on construction safety performance, which was indicated to be measured by another set of components such as safety planning, training, monitoring and auditing. This research is expected to make a considerable contribution to the safety studies in the construction industry and expected to guide construction firms to improve themselves in terms of lacking capabilities and develop appropriate strategies for technology use. The model proposed is expected to be used as a bridge between theory and practice to influence new studies. The model developed can further be used by industry practitioners to devise and develop new strategies and make sound decisions to choose among a set of emerging technologies. This way companies could improve their safety performance with the selection of proper technology knowing the most significant impact on safety performance.

Research framework

The framework proposed in this study involves the most important technologies for construction safety performance. In the initial phase, based on a comprehensive literature review that focused on studies regarding emerging technologies and construction safety, several components are derived. Emerging technologies and construction safety performance are determined as the main factors. After conducting pilot studies with five university professors and three experts, some components of the emerging technologies and construction safety performance were either combined or removed to reflect their corresponding factors. In the next phase, 12 components for emerging technologies and 5 components for construction safety performance were identified. These components are identified and explained below. Figure 1 reflects the relationship between emerging technologies and safety performance showing all components derived.

The theoretical basis for the developed components of emerging technologies is provided below.

Augmented reality (AR)

AR technologies are used in planning, training and supervision of construction safety, as in VR technologies (Park and Kim, 2013). However, unlike VR technology, which consists only of the virtual world and is isolated from the real world, AR is a technology that combines the virtual world with the real world (Afzal *et al.*, 2021; Haller, 2006). There is strong evidence in the literature that the use of AR in construction safety applications increases and improves safety (Kim *et al.*, 2019). The combined use of AR and information technology provides information to differentiate between standard safety needs and unsafe field environments. For example, if AR devices are integrated into the helmet, fire, smoke, weather conditions, etc. can identify situations (Oke and Arowoiya, 2021). Several researchers have recently stated that the use of AR contributes to construction safety training (Kim *et al.*, 2019; Placencio-Hidalgo *et al.*, 2022; Wang and Dunston, 2007), working conditions (Le *et al.*, 2015b; Talmaki *et al.*, 2010; Zhou *et al.*, 2017) and safety management (Kim *et al.*, 2019).

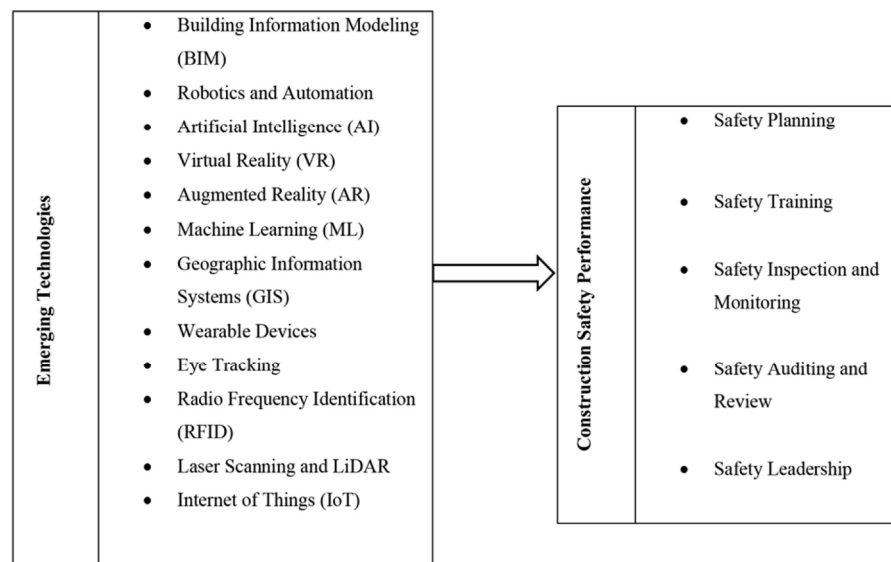


Figure 1.
Relationship between
emerging technologies
and safety
performance

Machine learning (ML)

ML is a generalization that enables input data and learned models to be used in later data (Najafabadi *et al.*, 2015). There is no programming in and ML and it aims to model, predict or control with computer programs using statistical techniques on existing data (Abioye *et al.*, 2021). Various studies have been carried out to identify risks in construction safety and to prevent accidents by using one or more of the ML methods such as Bayesian network, genetic algorithm, neural network and support vector machine (Gao *et al.*, 2022; Koc *et al.*, 2021; Lee *et al.*, 2020; Nayak *et al.*, 2022; Sarkar *et al.*, 2019).

Geographic information system (GIS)

Various factors such as environmental conditions, field topography and thermal comfort affect worker safety. However, these elements cannot be modeled with BIM. Issues such as making site drainage plans against flood risk, providing thermal comfort, or making a route plan with different transportation routes should be included in the safety planning (Bansal, 2011). Various research studies prove the use of GIS in accident prevention procedures and especially in safety plans (Bansal, 2011; Manase *et al.*, 2011).

Wearable devices

Wearables have great potential for collecting and analyzing real-time and results-oriented data about construction workers (Awolusi *et al.*, 2018). According to Nnaji *et al.* (2021), wearable devices are used for physiological monitoring and environmental sensing. Although these devices are seen as an important approach to physical data collection in the construction industry, they have little use in the psychological field (Guo *et al.*, 2017). Various studies have investigated the use of wearable technologies to determine workers' psychological conditions (Guo *et al.*, 2017) and physical conditions (Essa, 2000; Hwang and Lee, 2017; Jeon and Cai, 2021; Lee *et al.*, 2021) in worker health and safety in the construction industry.

Eye tracking

Eye tracking is a technique used to measure the direct and sustained attention of the workers. Uncertainties at the construction sites, which are the active working areas of the construction industry and safety audits related to environmental perception encourage eye-tracking studies in construction safety (Hasanzadeh *et al.*, 2018). In the construction industry, research is carried out using eye tracking technology in hazard recognition (Hasanzadeh *et al.*, 2017a; Jeelani *et al.*, 2019; Xu *et al.*, 2019), risk identification (Czarnocka *et al.*, 2020; Park *et al.*, 2022), accident prevention (Hasanzadeh *et al.*, 2017b, 2018) and safety training (Bükrü *et al.*, 2022; Olayiwola *et al.*, 2020).

Radio frequency identification (RFID)

Detection technologies such as RFID have great potential for ensuring safety, quality and efficiency in the construction industry (Arabshahi *et al.*, 2021). With radio waves, RFID can identify objects and read digital data without contact. Thanks to this technology, the use and suitability of personal protective equipment can be controlled. Thus, RFID helps to ensure job safety. In addition, real-time, dynamic and remote monitoring can be done with RFID technology (Sun *et al.*, 2013). Studies have shown that RFID technology is beneficial in accident prevention (Jo *et al.*, 2017; Wu *et al.*, 2013; Yang *et al.*, 2012) and location detection (tracking) (Barro-Torres *et al.*, 2012; Kelm *et al.*, 2015; Ko, 2010; Lee *et al.*, 2014) in construction safety.

Laser scanning and LiDAR

A considerable portion of the accidents and deaths in the construction industry are caused by workers colliding with their equipment (Marks *et al.*, 2013). Especially in construction sites, applications have been developed to use laser scanning and LiDAR to detect blind spots of equipment using point cloud data (Marks *et al.*, 2013; Ray and Teizer, 2013; Teizer *et al.*, 2010). With the laser scanning technique, the workers can get the opportunity to early detect potential hazard zones and conditions that might turn into dangerous cases.

Internet of things (IoT)

The use of IoT based technologies in the construction industry has been a subject of interest for researchers today (Tabatabaee *et al.*, 2022). However, the proportion of IoT technologies in the safety management of real projects is still insufficient. Most of the work done is in the testing phase (Yeo *et al.*, 2020). These studies have generally focused on the use of IoT for accident prevention (Rey-Merchán *et al.*, 2021; Yang *et al.*, 2020; Yeo *et al.*, 2020) and hazard identification (Costin *et al.*, 2019; Li *et al.*, 2018; Thirugnanasammandamoorthi and Choi, 2021) in construction safety.

Safety performance

This study considers the components of safety performance as “Safety Planning”, “Safety Training”, “Safety inspection and monitoring”, “Safety auditing and review” and “Safety Leadership”. Each component is explained in detail below.

Safety planning

Planning is defined as the process in which what needs to be done is determined in advance (Labour Department, 2002). This component is the phase of planning all safety-related activities and identifying high-risk activities for the prevention of hazards. In addition, at this stage, a safety approach should be developed for the safety of the work area and necessary precautions should be defined (PMI, 2005). Safety planning is strongly related to safety performance (Chellappa *et al.*, 2019; Khalid *et al.*, 2021). Various research studies have already proven that technology plays a critical role in safety planning (Bansal, 2011; Chellappa *et al.*, 2019; Choe and Leite, 2017; Yap *et al.*, 2022; Zhang *et al.*, 2015).

Safety training

Safety training consists of activities such as arranging meetings for site safety, training workers on the use of safety equipment at regular intervals and following safety regulations (Demirkesen and Arditi, 2015). Previous studies provided solid evidence for the fact that safety training is directly related to safety performance (Abas *et al.*, 2021; Chellappa *et al.*, 2019; Moosa and Oriet, 2022; Shaikh *et al.*, 2020). Moreover, a considerable portion of studies revealed that using safety technologies in safety training increases safety performance (Bhoir and Esmaeili, 2015; Bükür *et al.*, 2022; Chellappa *et al.*, 2019; Guo *et al.*, 2017; Kim *et al.*, 2019; Le *et al.*, 2015a, b; Olayiwola *et al.*, 2020; Park and Kim, 2013; Placencio-Hidalgo *et al.*, 2022; Wang and Dunston, 2007).

Safety inspection and monitoring

The safety inspection program should be checked periodically to identify deficiencies and make improvements. For an effective audit program, managers should be provided with a built-in quality control and monitoring function (Labour Department, 2002). There is strong evidence provided by previous studies implying that safety monitoring is strongly related to safety performance (Abas *et al.*, 2021; Chellappa *et al.*, 2019; Khalid *et al.*, 2021;

Moosa and Oriet, 2022). According to most studies, improving safety inspection and monitoring makes safety technologies more effective and promotes their use (Chellappa *et al.*, 2019; Guo *et al.*, 2017, 2021; Okpala *et al.*, 2021; Rey *et al.*, 2021; Yap *et al.*, 2021).

Safety auditing and review

An audit or review is required to evaluate occupational safety performance. An audit or review enables the company to increase, maintain and improve its ability to mitigate risks. It also creates an effective, efficient and safe safety management system and a feedback loop during the audit or review planning phase (Labour Department, 2002). Safety auditing and review are directly related to safety performance (Moosa and Oriet, 2022; Shaikh *et al.*, 2020). Various research studies have investigated the effectiveness of audits or reviews in safety performance and management (Teo and Ling, 2006; Aksorn and Hadikusumo, 2008; Moosa and Oriet, 2022; Nielsen *et al.*, 2008; Yiu *et al.*, 2018).

Safety leadership

Safety leadership has a key role in construction safety management (Zhang *et al.*, 2018). Besides the increasing importance of safety leadership, its importance on safety performance is also of utmost importance (Ma *et al.*, 2018). Previous studies showed that safety leadership contributes to improving safety performance (Khalid *et al.*, 2021; Ma *et al.*, 2018; Martin and Lewis, 2014; Moosa and Oriet, 2022; Skeepers and Mbohwa, 2015).

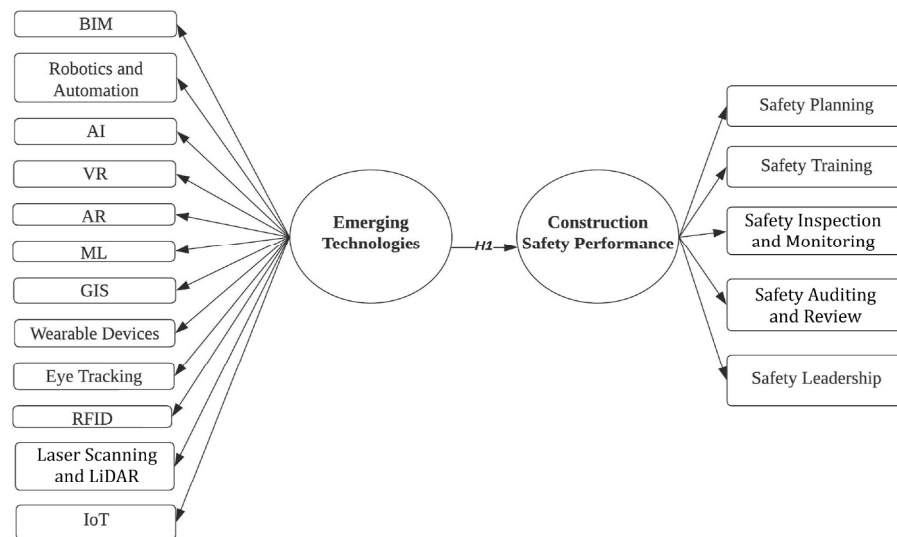
Despite the studies investigating the relationship between emerging technologies and safety performance, a better understanding of fundamental technologies and their impact on safety performance still appears as a challenge in the architecture-construction-engineering (AEC) industry. Several research studies provided that there has to be either decision frameworks or models to better analyze the relationship between some emerging technologies such as BIM and cloud computing in the industry (Gu and London, 2010; Volk *et al.*, 2014). Hence, this study visualizes the relationship between these technologies and safety performance by quantifying the effects. The following hypothesis is developed based on the evidence provided by the literature considering the impact of emerging technologies on construction safety management performance.

H1. Effective use of “emerging technologies” has a direct and positive effect on “construction safety performance”.

Figure 2 presents the conceptual framework developed for this study along with the valid indicators derived.

Research methodology

An online questionnaire was designed and administered to construction professionals in US construction firms based on the proposed framework. The questionnaires were addressed to large-scale engineering, construction and architecture firms. The targeted respondents were selected from the Engineering News-Record (ENR) 2022 Top 400 Contractors list. Of 350 questionnaires sent, 167 were returned, while 18 were online interviews resulting in a response rate of 48%. The 18 interviews were conducted to increase the response rate. The respondents were asked to fill in the questionnaire considering the emerging technologies adoption in terms of evaluating construction safety performance. The questionnaire consists of two main parts: (1) general information about the company, respondent and the project; and (2) variables related to the emerging technologies and construction safety. The respondents were requested to evaluate their performance in terms of practicing emerging technologies in relation to construction safety based on the listed variables using a 1–5 point

Figure 2.
Conceptual framework

Likert scale (1: very low, 2: low, 3: medium, 4: high, 5: very high). All respondents are senior-level managers of large-scale firms. According to the analysis of data collected in the questionnaire, the average firm age was found to be 43 years, where the average annual turnover is 189 million USD. The respondent profile consists of the contractors (58%) whereas the small portion comprises subcontractors (19%), structural designers (14%) architectural designers (5%) and owners (4%). The data involve residential projects (37%); infrastructure projects (22%); industrial construction (17%); water structures (13%) and other projects (11%). AMOS, an SEM tool, was used as the software package for analyzing the data collected from 167 questionnaires. SEM is a multivariate statistical methodology that utilizes a confirmatory approach to analyze a structural theory based on a phenomenon. SEM also tests hypotheses among observed and latent variables (Bollen and Long, 1993; Hoyle, 1995; Kline, 1998; Byrne, 2012). SEM is also known as causal modeling, causal analysis, simultaneous equation modeling, analysis of covariance (ANCOVA) structures, path analysis, dependence analysis, or confirmatory factor analysis (CFA). The reason why SEM was selected for this study is that it offers several advantages in terms of validity, reliability and complexity. SEM allows the use of several indicator variables for a construct simultaneously providing valid conclusions on the construct level. Moreover, SEM takes measurement error into account corresponding to the measurement error portions of observed variables, which in turn lead to unbiased conclusions. Finally, SEM provides several benefits to model and text complex patterns of relationships allowing the analysis of the multitude of hypotheses simultaneously as a whole (Werner and Schermelleh-Engel, 2009). SEM has been widely used in several research studies since 1980s (Xiong *et al.*, 2015). The SEM applications have been still accelerating and SEM has given reasonable results in especially in measurement and structural analyses so far (Bentler, 1989; Byrne, 2001; Hair *et al.*, 2006; Bagozzi and Yi, 2012). Therefore, it was used as a generic methodology to investigate the relationship. SEM typically consists of two parts, which are the measurement and the structural model (Kline, 1998). The measurement model presents the measurement of hypothetical constructs in terms of observed variables. The structural model specifies the causal relationships among the latent variables (Byrne, 2012). A structural model is

composed of the definition of the relationships among the latent variables and the specification of the measurement method of latent variables. SEM also necessitates testing the validity of the hypothesized constructs. Validity is simply defined as the extent to which the construct is measured by its instruments. In a SEM, there are two types of validity that must be achieved. Construct validity refers to the “degree of agreement of indicators hypothesized to measure a construct and the distinction between those indicators and indicators of a different construct” (Chen and Fong, 2012). The achievement of construction validity is essential for reliable model testing. Content validity refers to the degree to which the construct is represented by its indicators in its domain (Dunn *et al.*, 1994). Content validity must be also achieved for reliable model testing.

Findings

The questionnaire collected data regarding the level of success achieved in implementation for each component developed for each factor. Figure 3 presents the ratings for each component of emerging technologies. Abbreviations were used for each component (E1 = BIM, E2 = robotics and automation, E3 = AI, E4 = VR, E5 = AR, E6 = ML, E7 = GIS, E8 = wearable devices, E9 = eye tracking, E10 = RFID, E11 = laser scanning and LiDAR, E12 = IoT) and ratings are presented accordingly. The *x*-axis presents the components and the *y*-axis presents the level of performance achieved in each component by the respondents. According to Figure 3, it can be seen that the average rating of components is around 3.6, and Cronbach's alpha value is calculated as 0.889, which proves the reliability of the components in terms of explaining their construct. Moreover, the figure indicates that the respondents have shown greater success in BIM than in other technologies that they have been implementing.

Figure 4 presents the ratings for each component of construction safety performance. Abbreviations were used for each component (S1 = safety planning, S2 = safety training, S3 = safety inspection and monitoring, S4 = safety auditing and review, S5 = safety leadership) and ratings are presented accordingly. The *x*-axis presents the components and the *y*-axis presents the level of performance achieved in each component by the respondents. According to Figure 4, it is seen that firms are more successful in achieving “safety training” in their projects. It is also shown that firms satisfy “safety planning” and “safety training” objectives more than the other components.

Researcher judgment and insight were applied for content validity since there is no formal statistical test regarding this (Garver and Mentzer, 1999). The indicators of each construct were derived based on an in-depth literature review. Five university professors and three

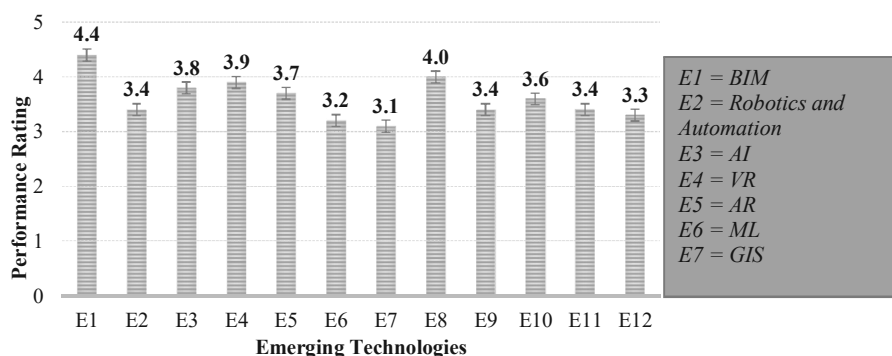
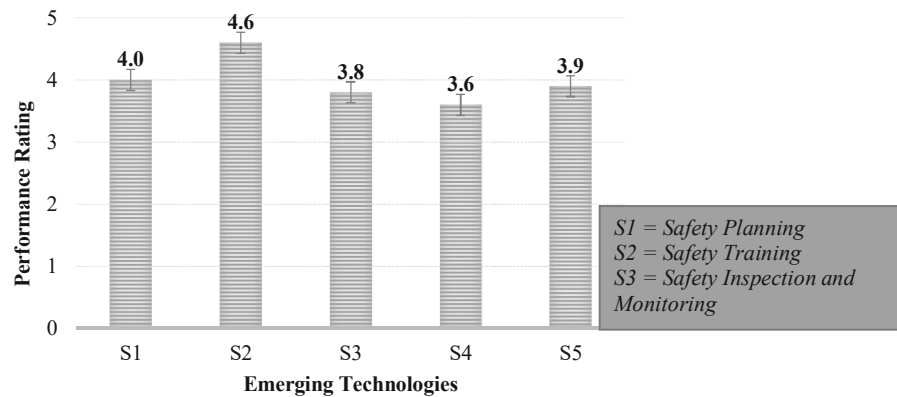


Figure 3.
Success level ratings
for emerging
technologies

Figure 4.
Success level ratings
for safety performance



experts helped to have the final list of components, where some components were either removed or merged to reflect a comprehensive list of components. For example, 3D printing and mobile technologies were omitted for the emerging technologies since these technologies are not among the most cited technologies, and experts further implied that these technologies are not very much practiced by the construction firms. For the safety construct, safety auditing and safety review were merged into a single component following the recommendation of the experts. Similarly, taking the recommendation of the university professors and experts, some components were embedded in the other components since they were revealed to be repetitive when shaping the core components list. In the initial list, 17 components were developed for emerging technologies and 9 for construction safety performance. After the in-depth interviews with professors and experts, 12 components were included in the final list for the emerging technologies construct, whereas 5 components were included for the construction safety performance.

Construct validity consists of convergent and discriminant validity and reliability. Convergent validity tests whether the items measuring a latent variable form a single latent variable. Convergent validity is evaluated by the careful examination of factor loadings and goodness of fit indices. Discriminant validity evaluates whether there is a statistically significant difference between the two measures by means of representing a construct, unlike the convergent validity. Discriminant validity might be investigated by looking at the intercorrelations between the measures of a construct (Byrne, 2012). To eliminate the statistically insignificant indicators from the model, examination of factor loadings is critical in CFA. This way, the internal reliability and fit indices are improved. Table 1 presents the factor loadings for the latent and constituent variables of the model. Factor loadings for each factor prove that all factors are well represented by their variables. Some slight differences were detected for some factors with respect to their placement on factors. For instance, BIM (factor loading: 0.986) was found to have a stronger association with construction safety performance than ML (factor loading: 0.783) and GIS (factor loading: 0.759), which were observed to be valid indicators too. A similar assessment criterion was utilized for the remaining factors leading to the conclusion that the variables for each factor are all valid indicators despite the slightly different placement of their corresponding factors. This can be further interpreted that the components determined for each construct are valid indicators representing their constructs very well.

Table 2 represents the reliability values and fit indices for the constructs of the framework. Reliability refers to the internal consistency of the constructs showing the magnitude of relations with the measure, where the error terms are excluded in a structural model (Bollen, 1989).

No	Model variables	Factor loadings	The impact of emerging technologies
<i>F1</i>	<i>Emerging technologies</i>		
V1	BIM	0.986	1333
V2	Robotics and automation	0.892	
V3	AI	0.875	
V4	VR	0.798	
V5	AR	0.801	
V6	ML	0.783	
V7	GIS	0.759	
V8	Wearable devices	0.858	
V9	Eye tracking	0.763	
V10	RFID	0.708	
V11	Laser scanning and LiDAR	0.711	
V12	IoT	0.753	
<i>F2</i>	<i>Construction safety performance</i>		
V13	Safety planning	0.895	
V14	Safety training	0.943	
V15	Safety inspection and monitoring	0.859	
V16	Safety auditing and review	0.804	
V17	Safety leadership	0.848	

Table 1.
Latent and constituent variables of the model

Index	Recommended value	F1	F2	Table 2. Reliability and fit indices for the constructs of the model
Cronbach's alpha	>0.7	0.943	0.899	
χ^2/df	<5.0	2.103	2.304	
RFI	>0.90	0.956	0.978	
CFI	>0.90	0.919	0.943	
TLI	>0.90	0.930	0.928	
RMSEA	<0.10	0.089	0.080	

The reliability test is assessed by Cronbach's " α " coefficient, where the construct reliability is satisfied when Cronbach's " α " coefficient exceeds 0.7 for all the constructs (Nunnally, 1978). Given the results of reliability analysis, it is concluded that constructs of emerging technologies and construction safety management performance are consistent. To test the goodness of fit, a Chi-square test was applied. Chi-square (χ^2) is utilized to reveal whether there is any significant difference between the actual and predicted matrices, where smaller values of χ^2 value represent a better fit. In AMOS, an SPSS tool, a ratio of χ^2/df (degree of freedom) is proposed as a fit measure. Despite the lack of consensus on χ^2/df value, a ratio lower than 5.0 is considered to be an acceptable range (Marsh and Hocevar, 1985). The analysis of the model generated a χ^2/df ratio of 2.987 and 2.906 for emerging technologies and construction safety performance, respectively. This leads to the fact that the data show a good fit for the model. Relative fit index (RFI) (Bollen, 1986), Comparative fit index (CFI) (Bentler, 1990) and Tucker–Lewis index (TLI) (Tucker and Lewis, 1973) are measures used to compare the proposed model to the independence or null model. The values of these indices lie between 0 and 1.0, where values approaching 1.0 represents a good fit. The root mean square error of approximation (RMSEA) (Steiger and Lind, 1980) is a parsimony-adjusted index, which includes a built-in correction for model complexity. Kline (1998) proposed a threshold value of Table 2 proves that the reliability of all constructs meets Nunnally's (1978) recommendation since all Cronbach's " α " values are above 0.7. It is shown that all fit indices are the acceptable ranges indicating that the measurement model

shows a good fit to the data. Finally, it is demonstrated that all values for RMSEA of all constructs are below the threshold value proving an acceptable fit for the data to the model. SEM tests the hypotheses between the validated constructs. In this respect, the relationship between emerging technologies and construction safety performance was assessed.

Figure 5 indicates the hypothesized relationships with path coefficients. In the figure, emerging technologies and construction safety performance are exogenous variables, where BIM, robotics and automation and AI represent endogenous variables. The arrows represent the direction of influence between the parameters of the framework where the numbers on the arrows show the path coefficients. Path coefficients are the equivalents of regression weights except that there is no intercept term in SEM. An interpretation guideline adopted from Murari (2015) is used for evaluating the strength of association between variables where the path coefficient ranging from 0.1 to 0.3 shows weak association; 0.3 to 0.5 (moderate) and 0.5 to 1.0 (strong). The findings of the study prove that there is a strong effect of emerging technologies on construction safety performance (0.846).

Table 3 shows the reliability values and fit indices for the model. Despite the lack of consensus on the threshold values of fit indices, some authors adopted a threshold value of 0.95 for most of the indices in SEM (Schreiber *et al.*, 2006; Lei and Wu, 2007), the authors of this study, therefore, adopted the threshold values recommended by the pioneers of SEM. The analysis results showed that Cronbach's " α " values were all found higher than 0.7 satisfying

Figure 5.
Construction safety
performance with
respect to emerging
technologies
framework with path
coefficients

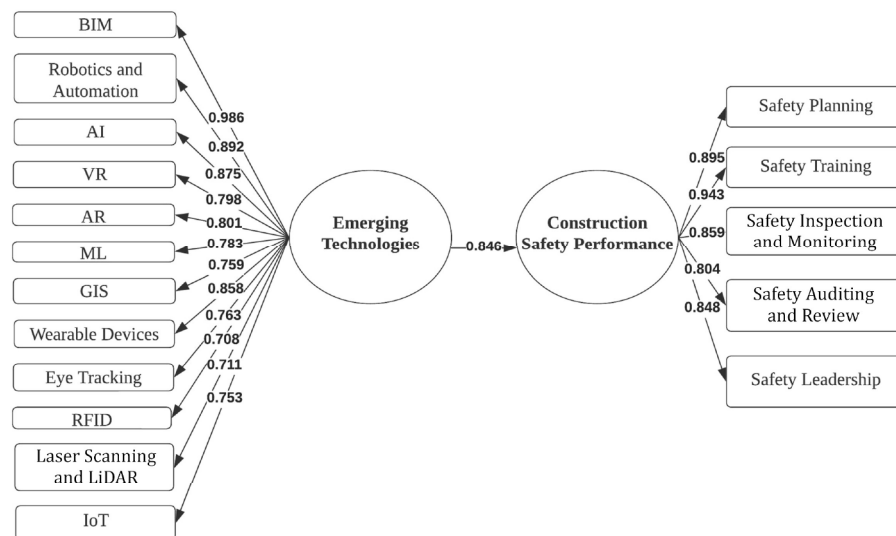


Table 3.
Reliability and fit
indices

Index	Recommended value	Model
Cronbach's alpha	>0.7	0.933
χ^2/df	<5.0	1.986
RFI	0 (no fit) to 1 (perfect fit)	0.963
CFI	0 (no fit) to 1 (perfect fit)	0.939
TLI	0 (no fit) to 1 (perfect fit)	0.927
RMSEA	<0.10	0.083

Nunnally's (1978) recommendation. RFI, CFI and TLI values were also found around 0.9 indicating a good fit of the model to the data. Moreover, RMSEA values were found below the threshold value with respect to Kline's (1998) recommendation. In the initial step, 186 responses were collected. However, responses having missing data or outliers were excluded from the analysis resulting in a response number of 167. The data were assessed for normality and normal distribution was observed. The data were further investigated in terms of multicollinearity, and it was detected that there is no multicollinearity, where the correlation matrices were assessed for all constructs since all intercorrelations were found below 0.90 with respect to Hair *et al.*'s (1998) threshold.

Discussion

The analysis of the model developed to investigate the relationship between emerging technologies and construction safety performance showed that there is a strong association between these two factors. Following the new trends and adopting technology is one of the most critical elements of successful project management. This in turn affects construction safety performance. This study revealed this critical chain between these two elements. Therefore, it is worth discussing the impact of each emerging technology determined in the model on the construction safety performance.

BIM is an important tool for construction safety performance. Provided with a high factor loading (0.986) in the model, it contributes to enhancing construction safety performance with its collaborative and cooperative environment as well as enhanced visualization and information-sharing mechanism. In this respect, Lu *et al.* (2021) developed a plug-in to calculate safety risks for a set of different design alternatives using Autodesk Revit software and concluded that this approach is a good remedy to optimize construction safety creating lower total fatality risk. Shen and Marks (2016) provided a near-miss visualization through the BIM user interface allowing construction personnel to detect near misses during a construction project by defining hazardous areas and near misses' frequency. This visualization makes the reporting of near misses possible through spatial location information. Enshassi *et al.* (2016) revealed that hazard identification and minimization and safety training and education are the most essential safety-related applications offered by BIM tools for improving safety performance in construction. As implied by previous research, BIM is highly effective in terms of contributing to safety performance. Therefore, technology implementors in construction companies might give special focus on BIM applications in terms of promoting safety performance through enhanced communication and visualization.

Robotics and automation have recently been applied in various construction projects. The analysis of the model revealed that it has a high impact on construction safety performance with a high factor loading (0.892). Robotics and automation can offer various advantages in terms of reducing the likelihood of accidents. Since construction operations are risky, the use of robots to replace humans in such operations (bricklaying or masonry) can lead to the safe delivery of projects in construction (Bahrin *et al.*, 2016). According to the recent research, it was implied that the use of robots and automation in construction operations can be highly effective in terms of limiting the exposure of workers to hazardous conditions while improving safety planning, awareness and communication (Okpala *et al.*, 2020). It was further mentioned that articulated robots can be of use in welding tasks, which are mostly conducted in high-risk situations (Karakhan and Alsaffar, 2019). Considering these, it is undeniable that robotics and automation have a powerful contribution to construction safety performance.

AI is found to be significant in terms of its impact on construction safety performance (factor loading: 0.875). AI represents the field of science, where computers perform tasks that would require human intelligence in normal conditions. AI can help enhance safety

performance using visual processing algorithms providing safety professionals a better risk monitoring and perception. AI can further help eliminate bulk amounts of visual data, where staff and situations are easily detected failing to meet safety standards (Chakravarthy, 2019). AI can improve the action recognition of workers and equipment as well as improve tracking accuracy (Abioye *et al.*, 2021). Bigham *et al.* (2018) further assessed the use of AI in construction safety and developed an AI platform, accordingly. Their platform was developed to improve construction safety through hazard identification at the pre-construction phase as well as helping to comply with OSHA codes for the identified hazards. Ayhan and Tokdemir (2019) further implied that AI-based systems can help to reduce the number of accidents in megaprojects in their study assessing safety using AI in megaprojects. As evidenced by several studies, AI can definitely enhance safety performance through different applications.

VR is another component that was found to be effective in terms of construction safety performance (factor loading: 0.798). VR is mostly used in safety training in construction projects and virtually implemented training can be highly effective in terms of promoting safety behavior (Zhao and Lucas, 2015). Sacks *et al.* (2013) tested the hypothesis of whether VR-supported safety training is more feasible and effective than traditional training conducted with conventional methods. They evaluated sixty-six subjects, where half of the subjects received conventional training and the other half received VR-enhanced training. They concluded that VR training was much more effective than conventional by means of keeping trainees' attention and concentration live. Moreover, VR training was found to be more effective over time in terms of cast-in-situ concrete works. Similarly, Le *et al.* (2015b) revealed that a social and collaborative VR platform helps to improve construction safety and health education. Given this background, it is observed that VR contributes to safety performance to a considerable extent.

AR is another important emerging technology in terms of affecting construction safety performance (factor loading: 0.801). Park and Kim (2013) mentioned that location tracking technology enhanced with AR has an important contribution in facilitating real-time and location-based field safety management, especially when used with mobile devices. Ahmed (2019) further implied that AR could be used as an effective tool for safety task scheduling to reduce the likelihood of ambiguity in tasks. Similarly, AR can be used for visualization purposes to enhance construction safety training (Le *et al.*, 2015b). Considering the benefits that the technology offers, one could claim that VR and AR are technologies that have a high impact in construction safety performance.

ML is found to be an essential component of emerging technologies in terms of impacting construction safety performance (factor loading: 0.783). There have been different applications of ML in construction safety so far. For example, Tixier *et al.* (2016) studied the use ML in accident prediction, and they concluded that construction safety should be both studied empirically and quantitatively. Poh *et al.* (2018) utilized ML to develop safety leading indicators for construction sites by predicting accident occurrence and severity. They suggested that ML algorithms can be effectively used to predict monthly safety performance at construction sites. Considering the growing need towards assessing safety performance, ML can be referred to as an effective emerging technology and can help enhance safety performance through proper forecasting.

GIS is another important technology in terms of promoting safety performance. Bansal (2011) implied that GIS can be effectively used in construction safety planning, where 4D modeling, geospatial analysis and topography modeling are utilized to develop a safe execution sequence. He further added that if a hazardous situation occurs in a planned sequence, it may be corrected through GIS before the actual implementation. Bai *et al.* (2015) further implied the use of GIS in improving the quality of safety in different stages of construction work. Bansal and Pal (2007) assessed the use of GIS in building cost estimation

and visualization implying that safety can be promoted with such use. As evidenced by several studies, the impact of GIS in terms of promoting safety performance was found to be significant with a factor loading of 0.759.

Wearable devices are effective means of construction safety, where they help to protect worker health and safety. Awolusi *et al.* (2018) highlighted the critical role of wearable devices in terms of personalized safety monitoring. Ahn *et al.* (2019) further listed several use cases of the wearable technologies such as measuring kinetic movement, skin response, cardiac activity, muscle engagement and eye movement, which might be of critical importance in worker health and safety. They also implied the use of sensors in preventing falls. Nnaji *et al.* (2021) mentioned the uses of wearable technology in terms of physiological and environmental sensing indicating the essential role of such technologies in improving worker health and safety. Provided with a factor loading of 0.858, such technologies help to prevent the likelihood of construction accidents and set up personalized systems to protect construction workers from being involved in accidents.

Eye tracking is an effectively used technology in construction safety. Recently, the eye tracking studies mostly focused on hazard recognition, risk identification, accident prevention and safety training (Jeelani *et al.*, 2019; Park *et al.*, 2022; Olayiwola *et al.*, 2020). Eye tracking was found to be a significant parameter in terms of affecting safety performance (factor loading: 0.763) (Hasanzadeh *et al.*, 2017a, b) prove that eye tracking is a useful technique to improve worker training and preparedness in terms of creating safer working conditions as well as detecting workers at risk and enhancing the effectiveness of training programs. Given this background, one might claim that using eye-tracking technology results in improved safety performance.

RFID is an important contributor to safety performance in construction projects. RFID helps to read digital data without contact and can identify the object with radio waves allowing the use of personal protective equipment in an efficient manner (Sun *et al.*, 2013). The impact of RFID on construction safety performance was found to be significant with a factor loading of 0.708. However, this impact was relatively less than the other emerging technologies listed above. This might stem from the fact that RFID requires some sort of special expertise in implementation, and it is considered to be costly (Lu *et al.*, 2011). On the other hand, the benefits of using RFIDs in accident prevention and location tracking have already been proven in various studies (Jo *et al.*, 2017; Lee *et al.*, 2014). As evidenced by various studies, one might claim that RFID is an effectively used technology to promote construction safety.

Laser scanning and LiDAR are trending technologies in terms of construction site safety. Its impact on construction safety performance was found to be significant in this study (factor loading: 0.711). These technologies are mostly known for their use in blind spot detection, which helps prevent accidents at construction sites (Marks *et al.*, 2013; Teizer *et al.*, 2010). The use of laser scanning has recently been trending in various construction projects since its benefits are proven. The high factor loading of the technology further indicates that it has a contribution to the safety performance.

IoT is the final technology developed to explain emerging technologies construct. Its impact on construction safety performance is significant with a factor loading of 0.753. Despite the limited number of studies regarding IoT and safety, there are growing efforts toward researching this link (Yang *et al.*, 2020; Yeo *et al.*, 2020). IoT is an effective technology, especially for hazard identification. Therefore, its potential in improving safety performance cannot be discarded.

This study indicated the clear link between emerging technologies and construction safety performance with a detailed discussion of each emerging technology in construction safety. Next section provides conclusions and future recommendations for upcoming studies.

Conclusions

This study investigates the impact of emerging technologies on construction safety performance. In this respect, a set of technologies such as BIM, VR, AR, wearable devices and IoT were identified. A total of five components representing construction safety performance were further identified. To measure the impact of emerging technologies on construction safety performance, a questionnaire was designed and administered to construction professionals. To enhance the reliability and increase the response rate, semi-structured interviews were conducted with industry executives. The content of the questionnaire was shaped in accordance with the opinions of the industry experts and academics. A total of 167 responses were reached. A SEM was first developed to test the hypothesis developed to measure the relationship between emerging technologies and safety performance. The questionnaire data and the SEM were analyzed using the AMOS tool of SPSS software.

The analysis of the structural model proves that there is a positive and significant relationship between emerging technologies and construction safety performance. Moreover, the factor loadings for each factor were found to be high indicating a good representation of the construct by the components developed. Among the technologies, BIM, robotics and automation, AI, and wearable devices were detected to be the most significant technologies in terms of impacting safety performance. On the other hand, the study had some limitations such as sample size and targeted respondents. The results might change with different sample sizes and a group of respondents. However, the average turnover of companies that participated in the questionnaire and company size is detected to be large. Therefore, this might be considered a good indication in terms of representing the industry trends and dynamics for using emerging technologies towards using construction safety performance.

This study recommends the exploration of new models to investigate the relationship between emerging technologies and construction safety. For example, a model investigating the relationship between BIM and safety training could be of interest. The results of this study are guiding researchers in this respect to explore such relationships. The models analyzed with different methodologies then could be compared with the results of this model proposed in the study. Moreover, industry practitioners and academics can benefit from the findings of this study to observe which technologies are mostly emerging and why some technologies are difficult to be adopted. This might increase the potential to develop strategies to best apply such technologies in construction organizations.

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