Journal Pre-proof

Technologies for safety and health management in construction: Current use, implementation benefits and limitations, and adoption barriers

Chukwuma Nnaji, Ali A. Karakhan

PII: S2352-7102(19)32856-6

DOI: https://doi.org/10.1016/j.jobe.2020.101212

Reference: JOBE 101212

To appear in: *Journal of Building Engineering*

Received Date: 15 December 2019

Revised Date: 19 January 2020

Accepted Date: 21 January 2020

Please cite this article as: C. Nnaji, A.A. Karakhan, Technologies for safety and health management in construction: Current use, implementation benefits and limitations, and adoption barriers, *Journal of Building Engineering* (2020), doi: https://doi.org/10.1016/j.jobe.2020.101212.

Author Statement

Chukwuma Nnaji: Conceptualization, Methodology, Formal Analysis, Writing – Original draft preparation

Ali Karakhan: Conceptualization, Literature Review, Writing- Reviewing and Editing

Technologies for Safety and Health Management in Construction: Current Use, Implementation Benefits and Limitations, and Adoption Barriers

Chukwuma Nnaji [1] and Ali A. Karakhan [2]

Abstract

The adoption and implementation of innovative solutions is an effective means to improve construction safety performance. The use of technology as a preventive tool for stemming the observed disproportionate rate of worker injuries and fatalities in the construction industry as compared with other industrial sectors has gained substantial attention over the last two decades. Previous studies have highlighted the need to advance the state of knowledge regarding the usefulness and utility of technologies for safety and health management in construction as well as factors that limit and prevent technology use in the construction industry. This paper aims to fill this gap in knowledge and practice by (1) identifying technologies used for safety and health management in the construction industry and assessing the current rate of use within the construction industry; (2) highlighting the benefits and limitations of using technologies for safety and health management, and (3) identifying the critical barriers to adopting technologies for safety and health management and propose strategies to overcome such barriers. To achieve the research aims, a survey was conducted to collect relevant data on the topic. 102 construction practitioners with pertinent knowledge of technology as it is used within their organization responded to the survey. Results of the study suggest that although slight increase in technology for safety and health management in construction adoption and use transpired due to technology ability to improve safety conditions, a notable resistance regarding its continuous use remains an issue across the industry. The study findings provide invaluable information for industry practitioners and researchers regarding limitations of technology implementation and barriers of technology adoption as well as strategies to overcome such limitations and barriers. Overcoming technology implementation limitations and adoption barriers is expected to enhance the adoption of technology for safety management in the construction industry.

[1] Assistant Professor, Department of Civil, Construction, and Environmental Engineering, The University of Alabama, 3043 HM Comer, Tuscaloosa, AL 35487; Email: cnnaji@eng.ua.edu

[2] PhD Candidate, School of Civil and Construction Engineering, Oregon State University, 101 Kearney Hall, Corvallis, OR 97331; Email: karakhaa@oregonstate.edu

Keywords: Construction management; occupational safety and health, technology barriers, technology implementation

1.0 Introduction

The construction industry is a major contributor to the global economy – contributing approximately $10 trillion to the global Gross Domestic Product (GDP) (McKinsey Global Institute 2017). In 2015 and 2016, the construction industry contributed approximately 6.2% of the US GDP with more than $650 billion, while this contribution continues to grow (ABC, 2019). Thus, the construction workforce is highly important globally, and to the US economy. The welfare of the construction workforce could lead to improved productivity and work quality, thereby producing high-performance buildings and/or civil works. Producing high-performance buildings and/or civil works maximizes the experience of all citizens and boosts the national economy. By contrast, any negative challenge faced by the construction workforce affect their productivity, the quality of their work, and could eventually lead to undesired outcomes on the economy and the experience of the public. Accordingly, the welfare of the construction workforce should be maximized. However, such workforce faces unique challenges that negatively influence their welfare, particularly their physical safety. The construction industry loses hundreds of its workers annually due to workplace injuries and fatalities. In 2017, over 970 construction work-related fatalities were reported in the US construction industry (BLS, 2018). This high number yields a fatality rate of approximately 10 workers killed annually per 100,000 full-time employees in construction. According to the International Labor Organization (ILO), construction workers in developed countries across the globe are 3 to 4 times more likely to have a fatal accident at work than other industries. This number increases to 6 times more likely in developing countries (ILO, 2014).

To minimize the high number of workplace injuries and fatalities, numerous practices that range from behavioral to engineering safety approaches have been implemented in the construction industry over the last few decades. Behavioral approaches (Langford et al., 2000; Gambatese et al., 2016; Azeez et al., 2019) emphasize the idea of improving worker awareness regarding the hazards and the use of the maximum number of safety precautions in the workplace. Engineering controls (Rozenfeld et al., 2010) include adopting safety best practices (e.g., guard and safety rail systems) to prevent worker exposure to hazards. However, safety performance in the construction industry remains poor.

Researchers continuously search for alternative strategies and practices that could significantly improve safety performance in the construction industry. An examination of the most recent publications on construction safety (Awolusi et al., 2018; Li et al., 2018; Howard et al., 2018; Jebelli et al., 2019; Ahn et al., 2019) reveal a clear trend on the utilization of technology for safety management. Zhou et al. (2013) stated that publication on the utilization of technology for safety management has increased by approximately three times from the early 2000s to the early 2010s. This rate has been sustained through the last decade (2010 – 2019) as well (Nnaji et al. 2019a; Mihic et al. 2019). Research on utilizing technology for safety and health management has increased because of technologies can create multiple safety benefits by recognizing workplace hazards that are not typically feasible for workers and eliminating workplace hazards early in the project lifecycle. In general, this study aims to draw upon current research efforts on this topic and maximize the applications of technology for occupational safety and health (OSH) management in the construction industry. In line with previous research (Nnaji et al., 2019b), a technology for safety and health management refers to information technology, digitalization, and sensing devices used to monitor and improve safety and health management and/or safety performance in the construction industry. These technologies can be applied as a primary or secondary function to either protect workers from hazards (i.e., control or eliminate hazards) or help identify/recognize workforce hazards (i.e., utilizing virtual reality for hazard identification and recognition). For instance, technologies such as wearable sensing devices and exoskeletons are primarily used to enhance OSH management but can also improve worker productivity (Awolusi et al. 2018; Kim et al., 2019). Similarly, the primary function of Building Information Modeling (BIM) is to enhance productivity through effective information sharing and communication, but BIM can also be can also be utilized to improve worker safety and health management (Martinez-Aires et al., 2018).

2.0 Background

2.1 Occupational Safety and Health Management in Construction

Managing OSH in construction is a critical factor of the success of any construction project. Safety and health incidents negatively impact schedule, quality, and cost of the project as well as employee morale, company reputation, insurance premiums, and so forth (Asanka and Ranasinghe 2015; Tang et al. 2004; Leung et al. 2015). Such negative outcomes could not only impact construction workers and their organization but could also affect the surrounding community or entire society in a destructive manner (Asanka and Ranasinghe 2015). The hierarchy of controls is typically used in construction for OSH management. The hierarchy of controls is a system comprising different levels of control to mitigate workplace hazards and manage OSH (Manuele 2005; Popov et al. 2016).

To be specific, the hierarchy of controls comprises of five levels [elimination, substitution, engineering, administration, and personal protective equipment (PPE)] ranging from the most effective to the least effective in terms of mitigating workplace hazards. Eliminating and substituting the hazards e.g., substituting hazardous emitting materials with zero emitting materials) are considered most effective because they physically remove all or part of the hazards (Manuele 2008; CDC 2020). Engineering controls (e.g., machine guarding, guardrails, barricades, and fall arrest systems) are considered the second most effective according to the hierarchy of controls (Manuele 2008; CDC 2020); they isolate workers from the physical hazards but do not eliminate or reduce the physical hazards. Finally, administrative controls (e.g., safety signage and training) and PPE (safety footwear and eyewear) are considered least effective in terms of mitigating workplace hazards (Manuele 2008; CDC 2020). Administrative controls improve worker awareness of the hazards but do not reduce the physical hazards, and PPE is used to minimize the impact of the hazards in case of an incident without mitigating the physical hazards itself (Manuele 2008; Popov et al. 2016). The next section will discuss how different construction technologies could be used for safety management in construction. These technologies can provide different types of hazard control, ranging from elimination to administrative, depending on type and functionality of the technology used.

2.2 Application of Technology for Safety and Health Management in Construction

The application of technology in the construction industry has been receiving great attention in the last few decades. Most of the technologies were initially adopted and used to either improve the quality of the final product or efficiency of the construction process, both of which eventually lead to reduced costs and improved profits. These days, it is apparent that more and more construction technologies are currently being used for safety and health management (Zhou et al. 2013; Awolusi et al., 2018; Li et al., 2018; Hasanzadeh et al., 2018; Howard et al., 2018; Jebelli et al., 2019; Ahn et al., 2019; Nnaji et al., 2019b). These technologies can be used in different construction applications to mitigate workplace hazards.

As mentioned, several technologies could be used to help train workers to recognize workplace hazards by providing cases similar to real-life scenarios. In particular, mixed-reality simulation is used in practice to train construction workers and equipment operators on identifying and mitigating workplace hazards associated with construction tasks and machine operation (Cheng et al., 2019). To provide an example, one could consider the work of Li et al. (2012). Li et al. developed a multiuser-friendly virtual environment training tool that construction employers could utilize to train their workers regarding safe procedures for tower crane erection and dismantling. The developed tool provides a step-by-step procedure to perform erection and dismantling of a tower crane in a safe manner. All of the training is enabled through a virtual reality environment which exposes trainees to minimal- to zero-risk when learning about erection and dismantling procedure of tower cranes. Such a tool is an effective administrative control to help construction workers understand safety risks inhibited in tower crane erection and dismantling processes.

Importantly, utilizing technology for safety management could provide more effective controls (e.g., engineering controls) than simply training workers on how to identify hazards (i.e., administrative controls). Qi. (2013) and Ziyu et al. (2019) developed safety tools to identify and address potential construction hazards early in the project lifecycle, that is, during the design phase. Similarly, Zhang et al. (2013) developed a safety-rule checking platform that examines the building systems and automatically identify any potential workplace hazards. Once the hazard is identified and categorized, prevention measures are generated by the platform to eliminate the hazards from the design or mitigate the hazards during construction operations. The tool and platform described above utilize BIM to design for construction worker safety before beginning construction. Designing for construction worker safety ensures that a significant portion of the physical hazards is removed from the construction process which is the most effective method of hazard mitigation according to the hierarchy of controls.

Another technology emerging in the construction industry is wearable safety devices (WSDs); WSDs are receiving substantial attention within both industry and academia. WSDs are small wearables that workers can attach to their body, outfits, or accessories to monitor their health and/or improve their safety. These devices are highly effective, easy-to-use, and inexpensive safety tools (Awolusi et al. 2018; Nnaji et al. 2019b). To be specific, WSDs are used in construction to prevent musculoskeletal disorders of field personnel, prevent work falls, assess physical workload and fatigue level of field workers, evaluate hazard recognition abilities of both workers and managers, and monitor worker mental status (Hasanzadeh et al., 2018; Ahn et al. 2019). Various other technology applications for safety management exist but, for brevity, they are not described in the present study. Readers interested in more information on technologies used in practice for safety and health management are advised to review relevant articles in the reference list (Hasanzadeh et al., 2018; Li et al., 2018; Jebelli et al., 2019; Gheisari and Esmaeili 2019; Cheng et al. 2019; Ahn et al., 2019).

3.0 Research Goal and Objectives

As previously stated, this study aims to build on current research efforts regarding the intersection between technologies used in construction management and safety, and maximize the applications of technology for OSH management. Such maximization is not possible without understanding the benefits and limitations as well as the barriers of adopting technology for OSH management. Although several studies interchange limitations and barriers to represent factors that deter the use of a technology in the construction industry, these terms are not constantly synonymous. Barriers are factors that prevent organizations or individuals from adopting a technology (Stewart et al., 2004). Barriers are typically pre-adoption factors. Conversely, limitations are factors that limits the extended implementation of a technology - typically observed at the post-adoption phase of technology integration. These definitions are certainly not synonymous. To ensure the distinction between barriers and limitations, this study defines “barriers” as the factors that prevent the adoption and use of a safety and health technology, and “limitations” are factors that limit the use of technology already adopted. The factors that prevent people from adopting technologies used for safety and health management and those that limit its continuous use and utilization post-adoption should be identified for the successful implementation of technologies on a construction project for safety and health management.

To achieve the research goal presented above, the three primary objectives are set as follows:

1) identify available technologies for OSH management,
2) identify and rank the benefits and limitations of technologies for OSH management, and
3) identify and quantify barriers to adopting technologies for OSH management and propose solutions to overcome such barriers.

4.0 Research Methodology

To address the three objectives of this study, a multi-method research approach was adopted. The approach consists of a structured review and content analysis of the available literature on the topic and a survey of industry professionals. Both approaches used are described in detail below.

4.1 Literature Search Parameters

First, an integrative review of existing literature was conducted to identify the technologies currently used in the industry to improve worker safety and health, their applications, benefits, and limitations. An integrative review of literature is a comprehensive methodological approach of reviews that combines data from empirical and theoretical literature to develop a conceptual model, review evidence-based findings, and analyze concerns associated with a particular topic (Souza et al., 2010; Torraco, 2005). This review process has been adopted by previous construction-related studies to identify important factors that affect decision making when selecting construction contractors based on safety performance (Karakhan et al., 2018). Moreover, the review process has been implemented extensively as a tool for identifying barriers and benefits associated with using safety and health technologies in health-related fields (Bhattarai and Phillips 2017; Al-Ghareeb and Copper 2016). The review process in this study was adopted from Souza et al. (2010) and involves six phases, namely, (1) preparing the guiding questions, (2) sampling the literature (3) collecting data, (4) analyzing included studies, (5) discussing result, and (6) presenting integrative review. For brevity, the description of each phase is excluded in this manuscript but could be found in Souza et al. (2010).

Four primary questions guided the review process, namely, “What technologies are used for OSH management in the construction industry?” “What are the benefits of using these technologies in OSH management?” “What are the limitations associated with using these technologies in managing worker safety and health on a construction project?” and “What are the barriers that prevent companies from adopting these technologies for OSH management?” Subsequently, multiple databases, including Google Scholar and Scopus, and specific publishers such as American Society of Civil Engineers (ASCE), Taylor and Francis, Emerald, and Elsevier were utilized to search for and identify useful publications by using keywords associated with the guiding questions (e.g., “construction management”, “construction safety devices,” “safety innovations,” and “construction technologies”, and “worker safety and health”). For instance, when searching Scopus, the following search code was utilized:

(TITLE-ABS-KEY ("Construction Management" OR “Construction” OR "Civil Engineering” OR "Built Environment") AND TITLE-ABS-KEY ("Worker Safety" OR " Worker Health" OR "OSH" OR "Occupational Safety and Health" OR "OSH") AND TITLE-ABS-KEY (“Technology” OR "Innovation" OR "Device")) PUBYEAR > 2000 AND PUBYEAR < 2019.

Afterward, the identified publications were screened by focusing mostly on the title, abstract, and conclusions, as well as the figures and tables. If a publication was deemed relevant (that is, it contained a discussion on the application of safety/health technologies on a construction project), a further detailed examination of the content was performed to identify potential benefits, limitations, and barriers of adopting and using safety and health technologies. Publications with limited information on the use of safety and health technology or application of the technology for a different purpose other than OSH management were disregarded. Section 6.1 summarizes the technologies identified through this process. Moreover, Sections 6.2 and 6.3 discuss the identified limitations, benefits, and barriers.

4.2 Survey Development

After identifying safety and health technologies, a survey questionnaire was developed to investigate whether these technologies are currently used by contractors in practice. The survey also included questions to collect information regarding factors that affect the adoption and use of technologies for safety and health management in construction. The survey consisted of three primary parts.

In Part 1, the participants were asked to provide demographic information about their occupation, years of experience, company size, and the construction segment they are involved in. Part 2 provided a list of technologies identified through an integrative literature review. The participants were requested to indicate if their organizations have used, will use, or have no intention to use the reported technologies in OSH management. In Part 3 of the survey, particular attention was given to questions that can address the second and third objectives of this study.

To address Objective #2, the survey included specific questions pertaining to the benefits and limitations of implementing available safety and health technologies. These questions help identify the benefits and limitations of implementing technologies with respect to safety and health management and ranks them according to the reported frequency (i.e., count). Similarly, the survey included questions to identify barriers against the adoption of technologies, particularly with respect to safety and health management (Objective #3). In this case, the questions were formed using a five-point Likert scale (where 1 represents “Not Important” and 5 means “Very Important”) to ensure that the level of importance of each barrier can be determined. Determining such importance level can help construction organizations decide on priorities regarding the barriers that must be overcome and those that could be left for the future. Count data is beneficial for determining the frequency of several variables (Azeez et al., 2019), and the Likert-scale data provides information on the level of importance of certain variables (Delgado et al., 2019).

Prior to the distribution, four knowledgeable professionals vetted the survey questionnaire to verify content and face validity. The experts have an average of 12 years of experience in the construction industry and/or research. They provided feedback about the type of questions used and the wording of several questions. Their feedback was used to revise the survey content before sending it to the participants. This pilot testing ensured that any bias was minimized and that the survey content is consistent with industry technical terms.

4.3 Survey Dissemination

From a statistical standpoint and according to probability sampling, the sample size should be determined before survey distribution. Determining the correct sample size for a study ensures that the selected samples would provide information that could be generalized to the large population or at least provide an indication about a large population. For this study, the sample size was determined using Equation #1 as reported by Lohr (2008).

$$Sample\ size = \frac{Z^2 * p * (1-p)}{C^2}\ , \qquad \text{Eq. 1}$$

where, z = z-score corresponding to the confidence level; ρ(1 − ρ) = response variance; and c = confidence interval or margin of error. The z-score for this study is 1.96, which represents 95% confidence level. A 50% response variance and a 90% confidence level were selected in line with previous construction safety studies (Tymvios and Gambatese 2016; Azeez et al. 2019).

Incorporating all of these values in Equation #1 revealed that the sample size should be no less than 97 for the sample to be representative of the large population. Accordingly, the researchers targeted a sample size involving at least 100 participants. To guarantee that selection bias is minimized, the researchers hired a third-party (Qualtrics Panel) to select the sample size and administer the survey. Qualtrics Panel is a professional organization that develops and disseminates surveys. Qualtrics Panel identified a participation pool that included construction managers, project managers, and safety personnel who work for general contractors and subcontractors in different states across the United States. The participation was limited to these occupations (management) to enhance the quality of the information gathered. Furthermore, only individuals informed about safety and health technology used in their organization were allowed to participate in the survey. This criterion may have presented a selection bias by only allowing individuals familiar with technology to participate in the study. These participants were gathered from diverse construction segments, including industrial, heavy civil, commercial, residential, and marine sectors. Participation in the survey was voluntary. Qualtrics Panel distributed over 4,000 surveys to potential participants, and 157 participants responded to the survey as described in the next section.

5.0 Survey Participants and Demographics

A total of 157 participants across the United States responded to the survey. The researchers screened the responses to ensure that only high-quality responses were included in the study. First, the researchers removed all responses from participants with less than five years of construction experience. Next, the researchers verified that only workers who are knowledgeable of when their organization implemented technologies for OSH management and those with job titles that infer management involvement were included. Finally, the researchers eliminated responses that showed signs of straight-lining and responses completed under one-third of the average response time.

Following the quality checks, 102 responses were considered acceptable. These checks improved the reliability and validity of the study by removing irrelevant responses or responses from people with little experience on the topic. The participants were predominantly from general contracting organizations (90.20%). In terms of company size (by revenue), 33% of the participants are from small enterprises (less than 10 USD million in revenue), 59% are from mid-sized companies (11 USD million to 1 USD billion), and 8% are from large organizations. California, Florida, and New York contributed 63% of the responses received. However, all regions in the United States (Midwest, Northeast, South, and West) were represented. Table 1 summarizes the demographic information of the participants.

Prior to asking the participants about their opinion on the benefits and limitations of implementing the identified technologies, the participants were requested to indicate if they were familiar with the technologies used as part of the safety and health management process of their organizations. All respondents have been exposed to these technologies in some capacity, but approximately 86% of the respondents indicated that they currently use BIM and WSDs as part of their safety management process. Fifty-nine participants revealed that their organizations use several automation and robotics to improve worker safety. Given their level of familiarity with the technologies, the participants' responses appear to be backed by first-hand experiences using these technologies, thereby enhancing the quality of their contributions.

Table 1: Demographic information

	Demography	% response	n
Organization Type	General Contractor	90.20	92
	Sub-Contractor	3.92	4
	Consultants (designers and management)	5.88	6
	Total	100	102
Job Title	Construction Manager	60.78	62
	Project Manager	39.22	40
	Total	100	102
Experience (years)	5 - 10 years	58.82	60
	10 - 20 years	31.37	32
	More than 20 years	9.81	10

Total	100	102

6.0 Survey Results and Analysis

This section summarizes the key results obtained from the survey questionnaire. Three subsections are included to correspond to the three research objectives stated above.

6.1 Identification of Technologies for OSH Management in Construction (Objective #1)

This study identified several technologies that could improve worker safety and health as a primary or secondary function. Safety and health technologies identified in the extant literature include: *BIM (Tang et al., 2019), Mobile Devices Onsite (Martínez-Rojas et al., 2016), Unmanned Aerial Vehicles (Gheisari and Esmaeili,* 2019*), Laser Scanning and LiDAR (Karakhan and Alsaffar, 2019), WSDs (Awolusi et al. 2018), Photogrammetry (Tang et al., 2019), Exoskeletons/Exosuits (Kim et al., 2019), Artificial Intelligence (Chakkravarthy, 2019), Quick Response Codes (Tang et al., 2019), Radio Frequency Identification (Martínez-Rojas et al., 2016), Augmented Reality (AR) (Kim et al., 2017), Virtual Reality (VR) (Sacks et al., 2013), Camera Network Systems (Zhang et al., 2019), Digital Signage (Karakhan et al., 2018), and Robot and Automation (Tang et al., 2019).* A complete list of the safety and health technologies identified through the integrative literature review process can be found in the supplementary material.

The study participants were asked to indicate if they are currently using, have plans to use, or have no intention to use each technology. Table 2 summarizes the responses to these questions. The top three technologies used by construction contractor-participants (in terms of the number of contractors currently using the technology) for OSH management are BIM (count = 88, rate = 0.86), WSDs (count = 88, rate = 0.86), and Mobile Devices (count = 86, rate = 0.84). The technologies least used by the participants and their companies for safety management are AR (count = 67, rate = 0.66), VR (count = 65, rate = 0.64), and Robot and Automation (count = 59, rate = 0.58).

Table 2: Technologies used for OSH management (*n* = 102)

Technology	Abbrv.	Currently using		Will use in future		No intention to use	
		Count	Rate	Count	Rate	Count	Rate
Building Information Modelling	BIM	88	0.86	4	0.04	10	0.10
Wearable Sensing Devices	WSDs	88	0.86	8	0.08	6	0.06
Mobile Devices Onsite	MDO	86	0.84	7	0.07	9	0.09
Radio Frequency Identification	RFID	81	0.79	11	0.11	10	0.10
Laser Scanning and LiDAR	LSL	76	0.75	13	0.13	13	0.13
Quick Response Codes	QR	76	0.75	13	0.13	13	0.13
Camera Network Systems	CNS	76	0.75	16	0.16	10	0.10
Digital Signage	DS	75	0.74	14	0.14	13	0.13
Photogrammetry	PG	74	0.73	11	0.11	17	0.17
Exoskeletons/Exosuits	EXO	71	0.70	10	0.10	21	0.21
Artificial Intelligence	AI	68	0.67	17	0.17	17	0.17
Unmanned Aerial Vehicles	UAVs	67	0.66	15	0.15	20	0.20
Augmented Reality	AR	67	0.66	19	0.19	16	0.16
Virtual Reality	VR	65	0.64	19	0.19	18	0.18
Robot and Automation	RA	59	0.58	24	0.24	19	0.19

6.2 Identification and Ranking of Benefits and Limitations of Construction Technologies Used for OSH Management (Objective #2)

The researchers identified a list of potential benefits and limitations associated with using these technologies from multiple studies on the application of technology in the construction safety and health management (Karakhan et al., 2018; Tang et al., 2019; Karakhan and Alsaffar 2019; Awolusi et al., 2018; Hallowell et al., 2016; Li et al., 2018; Lin et al., 2011; Wang et al., 2018; Zhang et al., 2019; SmartMarket 2017: Navigant 2016). Tables 3 and 4 list the benefits and limitations, respectively. In these tables, NoO and RoO refer to "Number of Occurrences" and "Rate of Occurrences," respectively. NoO represents the number of participants who agreed that a given benefit or limitation is associated with a technology. RoO is the ratio of the NoO divided by the total number of participants revealing the fraction of responses who agree that a given benefit or limitation is associated with using a technology.

According to the responses received from the participants, improving worker awareness of a hazard had the highest frequency. Among the participants, 81%, which is a figure that is nearly 30% higher than the second ranked benefit, indicated that using these technologies improve worker awareness of hazards associated with on-site construction operations. This finding is consistent with those of previous studies that showed a notable increase in workers' abilities to identify and recognize hazards when using VR (Sacks et al. 2013), BIM (Karakhan and Alsaffar 2019), and AR (Kim et al. 2017). Only four benefits reached a RoO above 50%. These benefits are "improves worker awareness of hazards" (NoO = 83, RoO = 0.81), "help warn workers of workplace hazard" (NoO = 55, RoO = 0.54), "eliminate hazards during the design phase" (NoO = 55, RoO = 0.54), and "helps visualize hazards" (NoO = 55, RoO = 0.54). Although some technologies have been credited with enhancing near-miss reporting (Shen and Marks, 2015), only 25% of the respondents believe this assertion as true.

Table 3: Benefits of using technologies for OSH management (*n* = 102)

Benefits of safety and health technology	**NoO**	**RoO**
Improves workers awareness of hazard	83	0.81
Help warn workers of workplace hazard	55	0.54
Eliminate hazard during the design phase	55	0.54
Help visualize hazard	55	0.54
Improves effectiveness of safety training	40	0.39
Enhances accident investigation	39	0.38
Enhances injury reporting	36	0.35
Isolate workers from hazard	35	0.34
Enhances safety planning	35	0.34
Enhances communication between workers	33	0.32
Improves safety inspections	31	0.30
Enhances near miss reporting	26	0.25

Where NoO = Number of Occurence and RoO = Rate of Occurrence

The participants were also asked to rate the limitations of using technology in safety and health management. Table 4 summarizes the collected responses regarding the limitations of using technologies for OSH management in construction. None of the identified limiting factors received a RoO greater than 50%. Evidently, the highest ranked RoO was the extra cost associated with using a technology (NoO = 47, RoO = 0.46), followed closely by application inconsistency due to client demand (NoO = 44; RoO = 0.43). Most identified limitations (approximately 70%) were selected by at least 25% of participants, thereby revealing that they significantly affect technology implementation. The limitations with the lowest RoO are related to lack of decision support tools to help with the integration of these technologies (NoO = =13, RoO = 0.13) and the ability of a technology to create a liability concern for the contractor (NoO = 13, RoO = 0.13).

Table 4: Limitations of using technologies for OSH management (*n* = 102)

Limitations	NoO	RoO
Extra costs associated with technology	47	0.46
Decision to use varies with client	44	0.43
Required workers training may not be cost effective	32	0.31
Data security is not guaranteed	27	0.26
No central system for managing data captured	26	0.25
Workers may ignore prompts from devices	23	0.23
Aging workforce is resistant to change	23	0.23
Privacy of workers personal data is not guaranteed	19	0.19
Little or no known standards for operation	16	0.16
Little or no government regulations for use	16	0.16
It does not help in error prevention	16	0.16
Slim profit margins in the industry	15	0.15
Lack of decision support tools	13	0.13
Creates liability concerns	13	0.13

Where NoO = Number of Occurence and RoO = Rate of Occurrence

6.3 Identification and Quantification of Barriers for Adopting Technologies OSH Management (Objective #3)

Thirteen key barriers to the adoption of technologies for OSH management were identified from the literature review described in Section 4.1. Survey participants indicated that extensive upfront cost is the foremost barrier to the adoption of technology for safety and health management in the construction industry (mean = 4, SD = 1.09). "Limited opportunity(ies) to observe and try these technologies before adoption" had the lowest mean value (mean = 3.53, SD = 1.25). However, all identified barriers had a mean rating above 3.5. Therefore, all factors reported could have a significant effect on the decision whether to adopt a certain technology for OSH management (Nitithamyong and Skibniewski, 2007). To determine the relative importance of each barrier, the researchers adopted a mean normalization process from previous research (Ameyaw and Chan 2015; Adabre and Chan, 2019). Normalization generally involves assessing the importance of each factor relative to other factors being evaluated as shown in Eq. 2 below.

Mean Normalized Value (MNV) = (Actual Value – Min. Value) / (Max. Value – Min. Value). Eq. 2

Following thresholds from previous research (Adabre and Chan, 2019), factors with mean normalized values (MNV) equal to or above 0.5 are considered critical barriers. The authors followed past investigations by using standard deviation (SD) as a measure of the variation within responses to determine the consensus of the responses. Rogers and Lopez (2002) stated that a consensus is considered reached if the SD is below 1.64, as explained by the probability theory in statistics. Accordingly, any factor that has a MNV equals to or greater than 0.5 and a SD equals to or less than 1.64 is considered a critical barrier to the adoption of technologies for OSH management. Table 5 shows the results of the survey. Consensus was reached for all factors, and the only factors that reported MNV of less than 0.5, namely, "Organization prefers using existing processes to manage safety," "Lack of information on the effectiveness of safety and health technology," and "Limited opportunity(ies) to observe and try these technologies before adoption" are considered less significant barriers to the adoption of safety and health technology in the construction industry. Therefore, 10 critical barriers prevent the adoption of safety and health technology in construction (Table 5).

Table 5: Barriers to adopting technologies for OSH management (n = 96)

Barriers	Mean	SD	MNV	Rank
Extensive upfront investment required	4.00	1.09	1.00	1
Need for extensive training before achieving optimum performance	3.98	1.10	0.96	2
Concerns regarding the technical support availability	3.87	1.08	0.72	3
Doubts regarding the reliability of these technologies	3.86	1.29	0.70	4
Client rarely demands for their use	3.86	1.15	0.70	4
Difficulty associated with interoperability	3.83	1.12	0.64	6
Limited technology useful life	3.82	1.15	0.62	7
Need for extensive technical support to achieve optimum performance	3.82	1.08	0.62	7
Limited attributes and features	3.8	1.09	0.57	9
The technologies tend to be complex to use	3.78	1.19	0.53	10
Organization prefers using existing processes to manage safety	3.74	1.13	0.45	11
Lack of information on the effectiveness of safety and health technology	3.71	1.18	0.38	12
Limited opportunity(ies) to observe and try safety and health technologies	3.53	1.25	0.00	13

7.0 Discussion of Results

Previous studies have highlighted the relatively low level of technology adoption in the construction industry (CII, 2008). In fact, the construction industry is ranked as the second least digitized industry in the US (Agarwal et al., 2016). However, to improve project performance, there is an increasing impetus to integrate new technologies into construction operations (Loosemore, 2014). As technologies become more effective, pervasive and ubiquitous, stakeholders within the construction industry should embrace the use of technologies as a tool for enhancing project performance. Moreover, given the increasing need to move toward sustainable construction practices, the clamor for a safe work environment through enhanced integration of technology in OSH management is expected to increase. To facilitate this integration, the benefits and limitations of technologies used for OSH management, as well as the barriers for adopting these technologies for OSH management, should be understood. Thus, this study identifies and examines the benefits, limitations, and barriers associated with the use of technologies for OSH management. By providing construction stakeholders with a list of technologies used for OSH management across the industry and identifying and ranking benefits, limitations and barriers, construction companies can deepen understanding and further utilize proper technologies for OSH management. This understanding would eventually encourage increased adoption and usage of technologies on construction jobsites, especially among smaller contractors who are known to be more resistant to change, thereby improving safety performance throughout the industry.

7.1 Current Status of Construction Technologies Used for OSH Management

Results indicated that the construction industry, especially relatively large general contractors, is advancing with respect to the use of technologies for OSH management. Based on the survey responses, BIM, WSDs, and MDOs were used in 2018 by more than 80% of the companies surveyed. Interestingly, these companies are using the aforementioned technologies for OSH management and for other purposes. This outcome represents significant progress given that previous statistics indicated low percentages (SmartMarket Report, 2017). However, this deviation is likely due to the sample used in the present study. By focusing on participants with experience in the adoption and use of technologies for OSH management, the sample could be skewed towards more progressive construction organizations.

The use of these technologies exhibits numerous benefits for safety and management (Zhang et al., 2015; Wang, 2017; Cheng and Teizer, 2013; Awolusi et al. 2018). For example, BIM can be used to design for safety early in the project lifecycle by eliminating hazards from the design and improving design feature and constructability (Hayne et al., 2014; Zhang et al., 2015; Sebastian and van Berlo, 2010). Moreover, BIM can be applied in safety planning (Sulankivi et al., 2010), thereby enhancing safety communication (Ganah and John, 2015), and safety inspection (Zhang et al., 2013). Additional benefits attributed to utilizing these technologies is discussed in the next section.

Notably, the same survey revealed that Artificial Intelligence, Unmanned Aerial Vehicles, AR, VR, and Robot and Automation were used by less than 70% of the companies surveyed. Thus, approximately over half of the companies that do not use such technologies stated that they will start using them in the upcoming three years. Multiple studies have shown the potential of these technologies to generate radical improvements in safety performance in construction (Awolusi et al., 2018; Gheisari and Esmaeili 2019; Chakkravarthy, 2019; Kim et al., 2017; Sacks et al., 2013; Tang et al., 2019). Individuals who stated that their companies lack intention to use these technologies in the near future were mostly from small- and medium-sized companies that have specific scopes and limited budget for this type of investment.

7.2 Benefits and Limitations of Technologies Used for OSH Management

The survey responses indicate several benefits of using technologies for OSH management in the construction industry. However, not all survey participants have observed evidence of these benefits in practice. Therefore, several benefits were reported more frequently than others (Table 3). In particular, improving worker awareness of hazards, warning workers from potential hazards, eliminating hazards during design, and visualizing hazards were the top four benefits reported by more than 50% of the study participants. Notably, improving worker awareness of hazards was reported by over 80% of the respondents. This high percentage is likely driven by two factors. First, most technologies are used after the design is completed and during construction operations. Utilizing technology for safety after beginning construction means that, in most cases, only opportunities to identify and control workplace hazards are present as opposed to eliminating hazards from the workplace altogether before beginning construction. Second, many of the technologies reported in the construction industry are used for training purposes to improve worker awareness of potential onsite hazards. In general, given the aforementioned factors, this benefit of using technology for OSH management (i.e., improving worker awareness of hazards) was more frequently reported than other potential benefits.

By contrast, several benefits were reported only by few participants. For example, enhancing near-miss reporting was reported by 26% of the participants. The respondents contended that merely few technologies are being used to report and document on-site near-misses. Based on the majority of the responses, mobile devices, such as smartphones and tablet PCs, were used occasionally to report and document near-misses in construction projects. In addition, the traditional pen-and-paper method is used in most construction projects instead. This finding is consistent with those of previous research which showed that when technology is utilized for safety management, smartphones and tablet PCs are commonly used for near-miss reporting and visualization (Park and Kim, 2012).

Despite the benefits associated with the use of technologies in managing construction worker safety and health, several limitations of the reported technologies were also identified. The survey responses reveal that the cost of continuous use of technology, client demand, additional training needed, and data security are the top four limitations of the use of technology for OSH management in construction. For conciseness, only the top two limitations, namely, cost of continuous use of technology and client demand, which were reported by more than 40% of the study participants, are discussed in depth below.

The cost of using and maintaining a technology was a concern expressed by approximately half of the study participants. This cost differs from the capital cost of a technology (i.e., the money paid to purchase or obtain a technology), is related to the use and maintenance of a technology in practice and could be significant in some cases depending on the technology employed. Reportedly, over 80% of the cost of using a technology occurs after the initial purchase of the technology (NetworkAlliance, 2019). To demonstrate this fact, let us assume that a construction firm intends to use VR/AR technology for safety management. Purchasing a VR and AR headset with full features for construction use could cost as low as $500 (Okpala et al., 2020). However, the cost of supporting systems (e.g., game engine software) and hardware components (e.g., a laptop, tablet, and motion tracker) could easily exceed $5,000. Moreover, a developer must be hired to create an immersive test environment to effectively use the technology on-site, and this requirement entails significant costs (Okpala et al., 2019). The same is true with the use of WSDs and these devices are inexpensive to obtain but quite expensive to use and maintain over a specific period. Esola (2018) reported that an IoT-supported wearable device could cost $100 per clip-on device, with an additional networking cost of $12,000–24,000 per year. These costs may not prevent a large construction company from using a technology, say a VR, but would certainly influence the decision of a small enterprise to use or forgo the technology in construction safety application.

Lack of client demand was also reported by 43% of the participants as a limitation to using particular technologies for OSH management in construction. This limitation is mostly due to the fact that several clients may demand the use of specific technologies while discouraging the use of other counterparts. A few participants reported that their clients, either as owners or designers, typically refuse to participate in safety efforts when using BIM because of liability concerns that may arise in case of accidents during the construction phase of a project. This finding is consistent with those of numerous studies that reported that designers, for example, are oftentimes unwilling to participate in safety efforts because of multiple reasons including fear of liability and legal consequences (Torghabeh and Hosseinian, 2012; Gambatese et al., 2017a, Toole et al., 2017). The use of BIM in construction is associated with legal issues and risks (Foster, 2008). Given the information discussed above, client demand seems to highly influence the use of technologies for OSH and clients occasionally encourage the use of particular technologies.

7.3 Barriers to Adopting Technologies for OSH Management

Section 6.3 and Table 5 reveal 13 barriers to the adoption of safety and health technology in the construction industry. The top five barriers were related to "upfront investment," "required training," "availability of technical support," "doubt concerning technology performance," and "clients lack of demand" are discussed here in depth. These five barriers are emphasized because their ratings are relatively higher than the reminder of the barriers (i.e., MNV above 0.70). This section also includes strategies that could be used by industry stakeholders to overcome the reported key barriers to high levels of adoption of technologies for OS management in the construction industry.

7.3.1 Upfront Investment for Adopting Technologies for OSH Management

The upfront investment required to implement a technology was reported as the top barrier against the adoption of technology for OSH management in the construction industry. This outcome is particularly true for small- and medium-sized companies that may lack adequate budget for technology adoption and implementation (Acar et al., 2005; SmartMarket Report, 2017). While some of the technologies discussed in this study require limited capital investment, many of these technologies require significant upfront investment. For example, BIM, AI, and Robots and Automation necessitate the purchase of requisite software and hardware components and their implementation on-site. Before implementation in the field, trials are needed to ensure that the staff working on/with a technology completely understand the features and limitations of the technology and whether the technology is suitable for particular tasks. However, several technologies entail reasonably low investment in terms of obtaining the technology itself. For instance, the cost of obtaining UAVs and WSDs are fairly reasonable. Thus, supporting hardware/software components may be required and could sometimes be quite expensive, as discussed in Section 7.2.

7.3.1.1 Strategies to Reduce Upfront Investment for Adopting Technologies for OSH Management

Respondents indicated that the cost of using technologies for OSH management is the primary reason that limits the extended use of these technologies on construction projects. Although certain technologies examined in this study are multifunctional technologies (e.g., UAVs, LiDAR, and AI) that create a broad positive effect due to scale of use, the initial purchase cost and additional costs needed for implementing the technology within the safety domain is a concern for users. The importance of managing the purchase and implementation cost is further exacerbated by the relatively low profit margin observed in the construction industry and the lack of investment in technology integration and in research and development. To encourage contractors to use these technologies, vendors should consider adjusting their business models to limit the upfront cost of using these technologies. A subscription-based model or a monthly payment structure over a given period may be a preferred model given that contractors can adjust the periodical payments to match their typical billing cycle – moving most of the cost upstream. However, the periodic payments should be reasonable.

Insurance companies could also provide several incentives to contractors to promote the use of technologies that will reduce the frequency of workers drawing on workers compensation. This incentive could be a direct reduction of the purchasing cost (paying a fraction of the capital cost of the technology) or be applied as an insurance premium deflator. Apart from developing and implementing innovative strategies to reduce the cost associated with using these technologies, previous studies suggest that providing information on benefit–cost or return on investment (ROI) plays a role in encouraging the uptake of safety and health related technologies (Nnaji et al., 2019a). Vendors must provide accurate information on the ROI to contractors. This ROI process should be adaptable and account for the different characteristics of contractors and implementation strategies. For instance, Ironhand, a hand exoskeleton, provides an adjustable ROI calculator to help potential clients estimate the ROI of purchasing their technology (Bioservo, 2019). Similar to Thiess et al., (2013) and Sun et al. (2011), researchers should complement vendors' efforts by proposing ROI and cost-effectiveness frameworks for technologies used for OSH management.

7.3.2 Required Training Associated with Adopting Technologies for OSH Management

Required training for workers prior to using a technology was reported as the second barrier against adopting safety and health technologies in the construction industry. This finding is consistent with those in the literature. Furthermore, numerous studies reported that the level of training needed for workers before they use a technology is one of the primary obstacles of technology adoption in construction (Mitropoulos and Tatum, 1999; Al-Gahtani and King, 1999; Mitropoulos and Tatum, 2000; Martínez-Rojas et al. 2016). Martínez-Rojas et al. (2016) reported that the required training may present challenges for construction contractors who intend to adopt construction technologies such as BIM. Martínez-Rojas et al. found that these challenges can be significant and not readily overcome by small- and medium-sized companies with less than 100 employees. Notably, such training must be provided to every single employee joining the companies. Additional training may also be required as the technology is updated and the software components are upgraded.

Certain employees, particularly baby-boomers, may require additional training due to their lack of technological and digital literacy (Meyer, 2011). Meyer (2011) argued that young workers (e.g., millennials) require less training hours when it comes to technology; however, such workers typically have lower experience levels than old workers. Peansupap and Walker (2005) added that certain workers, particularly baby-boomers, may need training in accessing the internet, storing collected data, and using supporting software, which are required in using technologies in OSH management.

7.3.2.1 Strategies to Minimize Required Training for Technology Adoption for OSH Management

Several studies have highlighted that construction workers are resistant to change, including the adoption of a new technology (Sardroud, 2012; Oesterreich and Teuteberg, 2016). This research highlights the significance of training for infusing and diffusing technology. The study participants indicated that a key reason for the slow uptake of technologies used in OSH management is the extensive training required before workers acquire the necessary skills to use these technologies. Furthermore, participants also highlighted that the cost implication of such an extensive training could limit the use of a these technology on-site. Previous investigations on technology adoption have emphasized the important role of a trained worker on the successful adoption of a technology (Ozorhon and Karahan, 2016; Nnaji et al., 2019b).

The need for qualified and trained workers is central to successful safety and health technology adoption and implementation. Training should start with educating workers about the importance and usefulness of the technology. This education should include information on the effectiveness of a technology (case study examples should be used whenever possible), the potential effect of a technology on worker safety, and the overall impact of a technology on the organization and their outputs. In addition, workers should participate in a hands-on description of standard operating procedures. Workers' knowledge on technology implementation should be evaluated via written assessment, such as through an exit survey. Within a specific period, safety personnel should appraise each workers comprehension of the standard operating procedure in using safety tools, for instance, through behavioral-based safety assessment. Following processes which encourage continuous learning and improvement would likely provide the required reinforcement needed to effectively implement change management.

Moreover, to reduce the impact of the resistance associate with some baby-boomers, construction companies should strike a balance regarding the structure of the team working in adopting and implementing technologies to ensure an appropriate mix of highly experienced workers (baby-boomers, for instance) and those more familiar with technology use (Millennials or Centennials, for instance).

7.3.3 Availability of Technical Support for Use of Technology in OSH Management

Concern regarding the technical support availability from a manufacturer is the third top barrier against the adoption of technology for OSH management in construction. Previous studies have reported that the unavailability of round-the-clock technical support is a significant hindrance that prevents stakeholders from adopting a technology (Rogers, 2000; Inan et al., 2010). Such unavailability could lead to improper application of the technology or the cessation of work operations. Thus, substantial cost, schedule, and productivity implications could occur. Construction companies are attracted to technology because it can help them advance their performance outputs while minimizing total costs and schedule delays. When a company feels that a technology might negatively affect performance outputs (time, cost, and quality), it would most likely stop using the technology or would not invest in the technology in the first place (i.e., not adopt the technology to begin with).

7.3.3.1 Strategies to Avoid Unavailability of Technical Support for Technology Use in OSH Management

To ensure that adequate technical support is available from the technology vendor, construction companies should obtain all relevant information from the manufacturer before deciding to adopt and use a technology. Such a process would guarantee that no issues will arise from the unavailability of technical support for a technology. Any unavailability could mean that the company would face undesired outcomes as reflected in the schedule, cost, and/or productivity. To reiterate, a technology is adopted and implemented to improve performance outcomes (time, cost, and quality). Therefore, when adopting a technology that could negatively affect these performance outcomes, no motivation to adopt the technology would be present in the first place. If the manufacturer fails to provide 24/7 support services, then in house technical expert or a specialist software support organization (consultant) should be hired (Peansupap and Walker, 2005). These may be considered as more expensive option.

7.3.4 Technology Performance Concern (Durability and Effectiveness)

Although the cost of a technology is an important factor that influences adoption, the effectiveness and reliability of a technology used in managing OSH plays a critical role in convincing workers to use it (Nnaji et al., 2018a). Lee et al., (2013) and Lai (2017) highlighted the significance of the perception of technology performance in the successful adoption and diffusion of that technology. Widely used technology adoption theories and models such as Unified Theory of Acceptance and Use of Technology, technology acceptance model, and technology-task-fit hinge on the perception of technology usefulness (Venkatesh et al., 2003; Zigurs and Buckland 1998). Given that information provided by a technology (WSDs, for instance) could mean the difference between an accident and a near-miss, it is essential that technologies used as warning devices are effective, exhibit appropriate features, are devoid of false alarms, and durable (Nnaji et al., 2018a; Awolusi et al., 2018). As innovation laggards, contractors prefer to use technologies that have proven performance.

7.3.4.1: Strategies to Minimize Technology Performance Concerns

To ensure that stakeholders have sufficient evidence to make informed decisions, practitioners and researchers must develop detailed use-case studies for each technology. For instance, Novosel (2016), Marks et al. (2017), Gambatese et al. (2017b), and Shukurat (2019) provided detailed evaluations of work zone intrusion alert systems. These reports provide sufficient depth and breadth of information that can be used by the decision makers involved in technology integration. Moreover, reproducible evaluation methods should be developed to ensure that other stakeholders can replicate the experiments within different contexts (Nnaji et al. 2019a). Information generated from technology use cases should be disseminated through appropriate channels such as practice-oriented journals or trade magazines to guarantee that the information reaches those individuals involved in technology integration decision making.

7.3.5 Client Involvement

In line with previous research (Nnaji et al., 2019b), client or owner involvement is considered critical to adopting technologies used for OSH management. Clients are vital in setting the safety culture of a project (Shen et al., 2015). In most cases, contractors are compelled to place a premium on things that have significant value to a client to guarantee client satisfaction and repeat business. Moreover, contractors are likely to adopt and implement technologies for OSH management if the client requires the use of certain technologies in the contract and in the project specific safety plan. For instance, state Department of Transportation commonly require contractors (contractually) to use specific technologies to help manage the flow of traffic in the work zone. This requirement has led to the increased use of technologies for safety management, such as digital safety signs (portable changeable message signs and variable message signs, for instance), automated flagging systems, and portable traffic signs (Nnaji et al., 2018b; 2019a). However, in most cases, the client will absorb the cost of including such requirements.

7.3.5.1 Strategies for Improving Technology Use in OSH Management through Client Involvement

To enhance technology use for OSH management on construction projects, clients should consider including specific technology requirements in contracts or incentivize contractors who adopt innovative safety solutions. In addition, clients could opt to include technology use as a criterion when assessing a contractor's safety performance. Karakhan et al. (2018) described that the level of technology implementation in OSH management is a key component of a contractor's safety maturity and should be assessed by owners prior to selecting a contractor. This finding implies that contractors who use effective technologies for managing OSH be regarded as having a mature safety program, thereby reducing risk to accidents that could affect the completion time of a project. If clients choose to adopt a process similar to the model of Karakhan et al., then contractors will be compelled to adopt and implement additional technologies to increase their competitiveness.

8.0 Conclusions, Limitations and Future Studies

This study aims to provide essential information required to support the adoption of technologies for enhancing worker safety and health in the construction industry. In addition to identifying the technologies currently used by participating construction organizations for OSH management, this work presents a list of benefits and limitations that influence the continuous use of the identified technologies. Critical barriers that prevent contractors from adopting technologies for OSH management are also presented. Moreover, a survey of 102 experienced workers within the US construction industry was conducted to provide critical information on the factors that affect the adoption of technology for OSH management The survey results indicate that the main benefits associated by participants with using technology for managing OSH are "Improves workers awareness of hazard," "Help warn workers of workplace hazard," and "Eliminate hazard during the design phase." "Extra costs associated with technology use," "Decision to use varies with client," and "Required worker training may not be cost effective" were identified as the primary challenges faced by participants who use technologies for managing OSH on construction projects. The critical barriers that prevent construction organizations from adopting technologies for OSH management include "Extensive upfront investment," "Need for extensive training before achieving optimum performance," and "Concerns regarding the technical support availability from manufacturer." The outcome of this investigation provides guidelines for practitioners and consultants involved in integrating technology into an organization's safety management system. Practitioners can focus on the identified barriers for technology adoption and can implement the suggested strategies in Section 7.3 above to overcome such barriers. Manufacturers and vendors, in turn, should take note of the limitations being observed by users of these technologies and endeavor to provide solutions to these challenges.

Similar to any research, this study is subjected to multiple limitations that require further investigations. First, although participation in the study was optional, the respondents primarily consisted of individuals from organizations who already implement technologies for OSH management. This could present a selection bias and, therefore, the results of the study may not be generalized across the industry and may not represent the experience of all construction organizations. Future studies should acquire insights from organizations with limited use of technology in OSH management. The case study approach could be employed to elicit additional detailed information regarding the challenges faced by these companies when adopting technologies for OSH management. Nevertheless, this study provides useful information that could help construction organizations that currently consider the use of these technologies for OSH management. Second, this study did not identify the causal relationship between the benefits, challenges, and barriers and the individual or organizational propensity to adopt a technology. An empirical survey could be conducted to gain additional insights in this regard. Such relationship could be evaluated using structural equation modeling (SEM) or similar methods. Third, a similar process (SEM) could be adopted to identify the relationship between using these technologies and impact on leading and lagging indicators. Finally, this research focused primarily on the perspective of management employees given the important role they play in the decision to purchase and implement a technology in safety context. Given that previous studies suggest that successful technology adoption is a hybrid of top-down and bottom up approach (Nnaji et al 2019c), future studies should concentrate on the perspective of field workers in order to generate valuable information that will complement the knowledge provided in this study.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers

9.0 References

ABC. (2019). "ABC News Release." Associated Builders and Contractors). Available on https://www.abc.org/News-Media/News-Releases/entryid/9801/constructions-contribution-to-u-s-economy-highest-in-seven-years (Accessed Nov. 27, 2019).

Acar, E., Kocak, I., Sey, Y., and Arditi, D. (2005). "Use of information and communication technologies by small and medium□sized enterprises (SMEs) in building construction." *Construction Management and Economics*, 23(7), 713-722.

Ahn, C. R., Lee, S., Sun, C., Jebelli, H., Yang, K., and Choi, B. (2019). "Wearable Sensing Technology Applications in Construction Safety and Health." *Journal of Construction Engineering and Management*, 145(11), 03119007.

Al-Gahtani, S.S. and King, M. (1999), "Attitudes, satisfaction, and usage: factors contributing to each in the acceptance of information technology", *Behaviour & Information Technology*, 18(4), 277-297.

Asanka, W. A., & Ranasinghe, M. (2015). Study on the impact of accidents on construction projects. In 6th International Conference on Structural Engineering and Construction Management (58-67).

Awolusi, I., Mark, E., and Hallowell, M. (2018). "Wearable Technology for Personalized Construction Safety Monitoring and Trending: Review of Applicable Devices." *Autom. Constr*. 85: 96 - 106.

Azeez, M., Gambatese, J., and Hernandez, S. (2019). What Do Construction Workers Really Want? A Study about Representation, Importance, and Perception of US Construction Occupational Rewards. *Journal of Construction Engineering and Management*, *145*(7), 04019040.

Bioservo (2019). "Return on Investment - ROI" Available on https://www.bioservo.com/professional/return-on-investment-roi (Accessed Nov. 27, 2019).

CDC (Center for Disease Control and Prevention). (2020). "Hierachy of Controls" NIOSH. Available on https://www.cdc.gov/niosh/topics/hierarchy/default.html (Accessed on Jan. 9, 2020).

Chan, A. P. C., Darko, A., Olanipekun, A. O., ad Ameyaw, E. E. (2018). "Critical barriers to green building technologies adoption in developing countries: The case of Ghana." *Journal of cleaner production*, *172*, 1067-1079.

Chan, P., and Leicht, R. (2014). "The role of integrated project delivery elements in adoption of integral innovations." EPOC 2014 Conference

Cheng, J.; Chen, K.; and Chen, W. (2019). “State-of-the-Art Review on Mixed Reality Applications in the AECO Industry,” *J. Constr. Eng. Manage*., 146(2): 03119009.

DataInsider (2018). “The FFIEC Cybersecurity Assessment Tool: A Framework for Measuring Cybersecurity Risk and Preparedness in the Financial Industry”

Delgado, J. M. D., Oyedele, L., Ajayi, A., Akanbi, L., Akinade, O., Bilal, M., and Owolabi, H. (2019). Robotics and automated systems in construction: Understanding industry-specific challenges for adoption. *Journal of Building Engineering*, *26*, 100868.

ENR (2019). “A Match Made in Cyber Hell” Available on https://www.enr.com/articles/46832-construction-cybercrime-is-on-the-rise (Accessed Nov. 2, 2019).

Esola, L. (2018). “Construction market flooded with devices seeking to cut injuries in hazardous sector.” Available on https://www.chubb.com/microsites/chubb-construction/wearable-technology-in599construction.aspx (Accessed Sept. 07, 2019)

Foster, L. L. (2008). “Legal issues and risks associated with building information modeling technology” (Doctoral dissertation, University of Kansas).

Gambatese, J. A., Pestana, C., and Lee, H. W. (2016). “Alignment between lean principles and practices and worker safety behavior.” *J. Constr. Eng. Manage*., 10.1061/(ASCE)CO.1943-7862.0001209, 04016083.

Gambatese, J. A., Michael Toole, T., and Abowitz, D. A. (2017a). “Owner perceptions of barriers to prevention through design diffusion.” *Journal of Construction Engineering and Management*, 143(7), 04017016.

Gambatese, J. A., Lee, H. W., and Nnaji, C. A. (2017b). “Work zone intrusion alert technologies: Assessment and practical guidance” (No. FHWA-OR-RD-17-14). Oregon. Dept. of Transportation. Research Section.

Ganah, A. and John, G.A. (2015), “Integrating building information modeling and health and safety for onsite construction”, *Safety and Health at Work*, 6(1), pp. 39-45.

Gheisari, M., and Esmaeili, B. (2019). “Applications and requirements of unmanned aerial systems (UASs) for construction safety.” *Safety Science*, *118*, 230-240.

Hallowell, M. R., Hardison, D., and Desvignes, M. (2016). "Information technology and safety: Integrating empirical safety risk data with building information modeling, sensing, and visualization technologies". *Construction Innovation*, 16(3), 323-347

Hasanzadeh, S., Esmaeili, B., and Dodd, M. D. (2018). “Examining the Relationship between Construction Workers’ Visual Attention and Situation Awareness under Fall and Tripping Hazard Conditions: Using Mobile Eye Tracking.” *Journal of Construction Engineering and Management*, 144(7), 04018060.

Hayne, G., Kumar, B. and Hare, B. (2014), “The development of a framework for a design for safety BIM tool”, *Computing in Civil and Building Engineering*, pp. 49-56.

Howard, J., Murashov, V., and Branche, C. M. (2018). “Unmanned aerial vehicles in construction and worker safety.” *American journal of industrial medicine*, 61(1), 3-10.

ILO (2014). “Safety and Health in the Construction Sector- Overcoming the Challenges.” International Labor Organization.” Available on https://www.ilo.org/empent/Eventsandmeetings/WCMS_310993/lang--en/index.htm (Accessed on Jan. 07, 2020)

Inan, F. A., and Lowther, D. L. (2010). "Factors affecting technology integration in K-12 classrooms: A path model." *Educational Technology Research and Development*, 58(2), 137-154.

Jebelli, H., Choi, B., and Lee, S. (2019). "Application of wearable biosensors to construction sites. I: Assessing workers' stress." *Journal of Construction Engineering and Management*, 145(12), 04019079.

Karakhan A., Xu Y., Nnaji C., Alsaffar O. (2018) "Technology Alternatives for Workplace Safety Risk Mitigation in Construction: Exploratory Study". In: Mutis I., Hartmann T. (eds) *Advances in Informatics and Computing in Civil and Construction Engineering*. Springer, Cham

Karakhan, A. A., Rajendran, S., Gambatese, J., and Nnaji, C. (2018). "Measuring and evaluating safety maturity of construction contractors: multicriteria decision-making approach." *Journal of Construction Engineering and Management*, *144*(7), 04018054.

Karakhan, A., and Alsaffar, O. (2019). "Technology's Role in Safety Management" *Professional Safety Journal of the Anerican Society of Safety Professionals*, 43 - 45

Kim, K., Kim, H., and Kim, H. (2017). "Image-based construction hazard avoidance system using augmented reality in wearable device." *Automation in Construction*, *83*, 390-403.

Kim, S., Moore, A., Srinivasan, D., Akanmu, A., Barr, A., Harris-Adamson, C., Rempel, D.M. and Nussbaum, M.A., (2019). "Potential of Exoskeleton Technologies to Enhance Safety, Health, and Performance in Construction: Industry Perspectives and Future Research Directions." *IISE Transactions on Occupational Ergonomics and Human Factors*, pp.1-7.

Lai, P. C. (2017). "The literature review of technology adoption models and theories for the novelty technology". JISTEM-*Journal of Information Systems and Technology Management*, 14(1), 21-38.

Langford, D., Rowlinson, S. and Sawacha, E. (2000), "Safety behaviour and safety management: its influence on the attitudes of workers in the UK construction industry", *Engineering, Construction and Architectural Management*, 7 (2),133-140.

Lee, S., Yu, J., and Jeong, D. (2013). "BIM acceptance model in construction organizations". *Journal of Management in Engineering*, 31(3), 04014048.

Leung, M. Y., Liang, Q., and Olomolaiye, P. (2015). "Impact of job stressors and stress on the safety behavior and accidents of construction workers." *Journal of Management in Engineering*, 32(1), 04015019.Li, X., Yi, W., Chi, H. L., Wang, X., and Chan, A. P. (2018). "A critical review of virtual and augmented reality (VR/AR) applications in construction safety". *Automation in Construction*, 86, 150-162

Lu, W., Huang, G. Q., and Li, H. (2011). Scenarios for applying RFID technology in construction project management. *Automation in construction*, *20*(2), 101-106.

Manuele, F. A. (2005). Risk assessment and hierarchies of control. *Professional Safety*, 50(5), 33-39.

Manuele, F. A. (2008). Prevention through design addressing occupational risks in the design and redesign processes. *Professional Safety*, 53(10), 28-40.

Martínez-Aires, M. D., Lopez-Alonso, M., & Martínez-Rojas, M. (2018). Building information modeling and safety management: A systematic review. Safety science, 101, 11-18.

Martínez-Rojas, M., Marín, N. and Vila, M., A. (2016). "The Role of Information Technologies to Address Data Handling in Construction Project Management". J. *Comput. Civ. Eng.*, 701 2016, 30(4)

Mckinsey Global Institute (2017) "Reinventing construction through a productivity revolution." Available on <https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/reinventing-construction-through-a-productivity-revolution>(Accessed Jan. 07, 2020)

Meyer, J. (2011), "Workforce age and technology adoption in small and medium-sized service firms," *Small Business Economics*, 37 (3), 305-324.

Mitropoulos, P. and Tatum, C. (2000), "Forces driving adoption of new information technologies", *Journal of Construction Engineering and Management*, 126 (5), 340-348.

Mitropoulos, P. and Tatum, C.B. (1999), "Technology adoption decisions in construction organizations", *Journal of Construction Engineering and Management*, 125 (5), 330-338.

NetworkAlliance (2019). "Understanding technology costs." Available on https://networkalliance.com/understanding-technology-costs/ (Accessed Nov. 15, 2019).

Nitithamyong, P., and Skibniewski, M. J. (2007). Key success/failure factors and their impacts on system performance of web-based project management systems in construction. *Journal of Information Technology in Construction (ITcon)*, 12(3), 39-59.

Nnaji, C., Lee, H. W., Karakhan, A., and Gambatese, J. (2018a). "Developing a Decision-Making Framework to Select Safety Technologies for Highway Construction". Journal of Construction Engineering and Management, 144(4).

Nnaji, C., Gambatese, J., and Lee, H. W. (2018b). "Work zone intrusion: Technology to reduce injuries and fatalities". *Professional Safety*, 63(04), 36-41.

Nnaji, C., Gambatese, J., Lee, H. W., and Zhang, F. (2019a). "Improving construction work zone safety using technology: a systematic review of applicable technologies." Journal of Traffic and Transportation Engineering (English Edition).

Nnaji, C., Gambatese, J., Karakhan, A., and Eseonu, C. (2019b). "Influential safety technology adoption predictors in construction." *Engineering, Construction and Architectural Management.* Vol. 26 No. 11, pp. 2655-2681. https://doi.org/10.1108/ECAM-09-2018-0381

Nnaji, C., Okpala, I., and Kim, S. (2019c). "A Simulation Framework for Technology Adoption Decision Making in Construction Management: A Composite Model." In *Computing in Civil Engineering 2019: Visualization, Information Modeling, and Simulation* (pp. 499-506). Reston, VA: American Society of Civil Engineers.

Oesterreich, T. D., and Teuteberg, F. (2016). "Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry." *Computers in industry*, 83, 121-139.

Okpala, I., Nnaji, C. and Karakhan, A. (2020). "Utilizing Emerging Technologies for Construction Safety Risk Mitigation" *ASCE Practice Periodical on Structural Design and Construction Journal*. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000468

Park, C. S., and Kim, H. J. (2013). "A framework for construction safety management and visualization system." *Automation in Construction*, 33, 95-103.

Peansupap, V., and Walker, D. H. (2005). "Factors enabling information and communication technology diffusion and actual implementation in construction organisations." *ITcon*, 10(14), 193-218.

Popov, G., Lyon, B. K., and Hollcroft, B. (2016). "Risk assessment: A practical guide to assessing operational risks." John Wiley & Sons.

Qi, J., Issa, R. R., Olbina, S., and Hinze, J. (2013). “Use of building information modeling in design to prevent construction worker falls.” *Journal of Computing in Civil Engineering*, 28(5), A4014008.

Rogers, M. and Lopez, E. (2002). “Identifying critical cross-cultural school psychology competencies.” *Journal of school psychology*, 40(2), 115-141.

Rogers, P. L. (2000). “Barriers to adopting emerging technologies in education.” *Journal of educational computing research*, 22(4), 455-472.

Rozenfeld, O., Sacks, R., Rosenfeld, Y. and Baum, H. (2010), “Construction job safety analysis”, *Safety Science*, 48(4), 491-498.

Sacks, R., Perlman, A., and Barak, R. (2013). “Construction safety training using immersive virtual reality.” *Construction Management and Economics*, *31*(9), 1005-1017.

Sardroud, J. M. (2012). “Influence of RFID technology on automated management of construction materials and components.” *Scientia Iranica*, 19(3), 381-392.

Sebastian, R. and van Berlo, L. (2010), “Tool for benchmarking BIM performance of design, engineering and construction firms in the Netherlands”, *Architectural, Engineering, and Design Management*, 6(4), pp. 254-263.

Shen, X., and Marks, E. (2015). “Near-miss information visualization tool in BIM for construction safety.” *Journal of construction engineering and management*, 142(4), 04015100.

Shen, Y., Tuuli, M. M., Xia, B., Koh, T. Y., and Rowlinson, S. (2015). “Toward a model for forming psychological safety climate in construction project management.” *International journal of project management*, 33(1), 223-235.

SmartMarket Insight. (2019). “Using Technology to Improve Risk Management in Construction” *Dodge Data and Analytics*, Bedford, MA

SmartMarket Report. (2017). “Safety Management in the Construction Industry 2017.” *Dodge Data and Analytics*, Bedford, MA.

Souza, M. T. D., Silva, M. D. D., and Carvalho, R. D. (2010). “Integrative review: what is it? How to do it?” *Einstein (São Paulo)*, *8*(1), 102-106.

Stewart, R. A., Mohamed, S., and Marosszeky, M. (2004). An empirical investigation into the link between information technology implementation barriers and coping strategies in the Australian construction industry. *Construction Innovation*, 4(3), 155-171.

Sulankivi, K., Kähkönen, K., Mäkelä, T. and Kiviniemi, M. (2010), “4D-BIM for construction safety planning”, Proceedings of W099-Special Track 18th CIB World Building Congress, pp. 117-128.

Sun, C., Edara, P. P., Hou, Y., Robertson, A., and Smith, D. (2011). “Cost□Benefit Analysis of Sequential Warning Lights in Nighttime Work Zone Tapers.” University of Missouri, Report to the Smart Work Zone Deployment Initiative.

Tang, S. L., Ying, K. C., Chan, W. Y., & Chan, Y. L. (2004). Impact of social safety investments on social costs of construction accidents. *Construction Management and Economics*, 22(9), 937-946.

Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., and Gao, X. (2019). "A Review of Building Information Modeling (BIM) And The Internet of Things (IoT) Devices Integration: Present Status and Future Trends”. *Automation in Construction*, 101, 127-139.

Theiss, L., Pratt, M., Ullman, G., and Maxwell, S. (2014). “Evaluation of Cost□Effectiveness of Steady□Burn Warning Lights in Work Zones.” Transportation Research Record: *Journal of the Transportation Research Board*, (2458), 65□73. tool”, *Computing in Civil and Building Engineering*, 49-56.

Toole, T. M., Gambatese, J. A., and Abowitz, D. A. (2016). “Owners’ role in facilitating prevention through design.” *Journal of Professional Issues in Engineering Education and Practice*, 143(1), 04016012.

Torghabeh, Z. J., and Hosseinian, S. S. (2012). “Designing for construction workers' safety.” International Journal of Advances in Engineering and Technology, 4(2), 373.

Torraco, R. J. 2005. “Writing integrative literature reviews: Guidelines and examples.” *Hum. Resource Dev. Rev*. 4 (3): 356–367. https://doi.org/10 .1177/1534484305278283.

Tymvios, N., and J. A. Gambatese. 2016. “Perceptions about design for construction worker safety: Viewpoints from contractors, designers, and university facility owners.” *J. Constr. Eng. Manage.* 142 (2): 04015078. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001067

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

Wang, L.C. (2008), “Enhancing construction quality inspection and management using RFID technology," *Automation in Construction*, 17(4), pp. 467-479.

Wang, P., Wu, P., Wang, J., Chi, H. L., and Wang, X. (2018). “A critical review of the use of virtual reality in construction engineering education and training”. *International journal of environmental research and public health*, 15(6), 1204.

Zhang, S., Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C. M., and Teizer, J. (2015). “BIM-based fall hazard identification and prevention in construction safety planning.” *Safety science*, 72, 31-45.

Zhang, S., Teizer, J., Lee, J. K., Eastman, C. M., and Venugopal, M. (2013). “Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules.” *Automation in Construction*, 29, 183-195.

Zhang, Y., Luo, H., Skitmore, M., Li, Q., and Zhong, B. (2019). “Optimal Camera Placement for Monitoring Safety in Metro Station Construction Work”, *J. Constr. Eng. Manage. 145*(1), 1–13. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001584.

Zigurs, I., and Buckland, B. K. (1998). “A theory of task/technology fit and group support systems effectiveness.” *MIS quarterly,* 22(3).

Jin, Z., Gambatese, J., Liu, D., and Dharmapalan, V. (2019). “Using 4D BIM to assess construction risks during the design phase.” *Engineering, Construction and Architectural Management.*

Technologies for Safety and Health Management in Construction: Current Use, Implementation Benefits and Limitations, and Adoption Barriers

Highlights

- 15 technologies frequently used for safety and health management in the construction industry and labeled as effective are identified and investigated in the study.
- 12 benefits and 14 limitations associated with the use of technologies for safety and health management are summarized in the study.
- 13 critical barriers inhibiting the adoption of technologies for construction worker safety and health management are evaluated in the study.
- Effective strategies for overcoming existing adoption barriers are discussed in the study.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: