A BIBLIOMETRIC ANALYSIS OF DIGITAL TECHNOLOGIES USE IN CONSTRUCTION HEALTH AND SAFETY

Purpose: Construction is a risky industry. Therefore, organizations are seeking ways towards improving their safety performance. Among these, the integration of technology into health and safety leads to enhanced safety performance. Considering the benefits observed in using technology in safety, this study aims to explore digital technologies' use and potential benefits in construction health and safety.

Design/Methodology/Approach: An extensive bibliometrics analysis was conducted to reveal which technologies are at the forefront of others and how these technologies are used in safety operations. The study used two different databases, Web of Science and Scopus, to scan the literature in a systemic way.

Findings: The systemic analysis of several studies showed that the digital technologies use in construction are still a niche theme and need more assessment. The study provided that sensors and wireless technology are of utmost importance in terms of construction safety. Moreover, the study revealed that artificial intelligence, machine learning, building information modeling, sensors, and wireless technologies are trending technologies compared to unmanned aerial vehicles, serious games, and the internet of things. On the other hand, the study provided that the technologies are even more effective with integrated use like in the case of building information modeling and sensors or unmanned aerial vehicles. It was observed the use of these technologies varies with respect to studies conducted in different countries. The study further revealed that the studies conducted on this topic are mostly published in some selected journals and international collaboration efforts in terms of researching the topic have been observed.

Originality/Value: This study provides an extensive analysis of Web of Science and Scopus databases and an in-depth review of the use of digital technologies in construction safety. The review consists of the most recent studies showing the benefits of using such technologies and showing the

usage on a systemic level from which both scientists and practitioners can benefit to devise new strategies in technology usage.

Keywords: construction safety, digital technologies, bibliometrics analysis

INTRODUCTION

The construction industry is one of the hazardous industries when the number of work-related accidents, injuries, and fatalities is examined (Reiman et al., 2019; The Center for Construction Research and Training (CPWR), 2018; Demirkesen and Arditi, 2015; Goldenhar et al., 2001; Toscano et al., 1996). Specific characteristics of the construction industry such as fragmented structure, dynamic and complex nature of processes, and cultural variety of employees lead to several challenges regarding safety on construction sites (Liang et al., 2020). According to the report published by the Bureau of Labor Statistics (BLS) in 2019, a total of 5,333 fatal occupational accidents occurred in the USA, of which 1,061 were in the construction industry (U.S. Bureau of Labor Statistics, 2019). Similarly, 3,332 fatal accidents were reported in Europe in 2018, one-fifth of which originated in the construction industry based on the data taken from (Eurostat, 2020). In total, approximately one-sixth of fatal accidents occur at construction sites globally (Shohet et al., 2018; International Labour Organization, 2005). Leading causes of fatalities in the construction industry are falls, struck-by, caught-in/between, and electrocutions (OSHA, 2011).

Prevention of accidents is significant because the cost of human life is immeasurable. While the injuries and fatalities cause pain to employees and their families, they also cause delays in projects and cost overruns (Park et al., 2015). Injury costs can reach up to 15% of total construction costs (Hallowell, 2011). Further, the failure to provide safety may create legal consequences for construction companies (Holt, 2005). For these reasons, construction safety is one of the most important issues to be monitored and controlled (Park et al., 2015). Even though there are cornerstone studies encompassing safety and safety implementation in the construction industry, a comparative analysis of existing studies has not been evaluated thoroughly. Especially, the use of technology in construction safety has not been assessed well in many of the construction safety studies. However, the industry is dynamic and there is a growing need for transformation and adoption of new technologies, which is further articulated as Construction 4.0. Therefore, this study provides a bibliometrics review of existing studies on the topic of digital technologies in construction health and safety. The background of the research and methodology used is explained in the following sections.

RESEARCH BACKGROUND

The focus on construction safety research has considerably increased in recent years (Jin et al., 2019). Hence, a systematic literature review becomes vital to reveal novel findings, identify research areas and assist construction stakeholders to become familiar with the recent trends and implementations (Liang et al., 2020). Liang et al. (2020) conducted a bibliometric analysis to investigate construction safety management. They utilized data from the Web of Science database, including the time range from 1991 to 2016, and utilized CiteSpace software. Based on their analysis, they reported that one of the main topics within the construction safety management area is technology-driven management, which focuses on safety training, planning, and monitoring sub-topics. Jin et al. (2019) reviewed construction safety through bibliometric and scientometric analyses. They utilized the Scopus database and practiced VOSViewer software. Their research concluded that the use of information technology for construction safety is a fast-growing and progressing area for research. They further implied that Building Information Modeling (BIM), Virtual Reality (VR), Augmented Reality (AR), and data analysis have recently attracted significant attention compared to other technologies (Jin et al., 2019).

Following up the technological developments and adopting innovative approaches is one of the most effective methods to improve safety performance in the construction industry (Skibniewski, 2014). In the last 20 years, the use of digital technologies to reduce worker injuries and fatalities has received considerable attention (Nnaji and Karakhan, 2020). As the number of different safety applications in the construction industry has taken place in recent years, it has been observed that safety performance has increased considerably (Hinze et al., 2013). The use of information technologies provides many advantages such as data acquisition, fast access, active transfer, full presentation, and convenient information storage. Digital technologies help to improve safety planning, real-time hazard detection and warning, and management of accumulated safety knowledge (B. H. W. Guo et al., 2017). Many researchers have already investigated the application of these technologies before, during, and after construction accidents and they mentioned the successful results (Tsai, 2016). This brings the need for technology use to eliminate issues associated with the construction health and safety (Skibniewski, 2014). A systematic review of the literature on the use of these technological applications in construction health and safety is important in terms of revealing current research areas and related research findings and catching new trends (Akinlolu et al., 2020; Liang et al., 2018; Zhou et al., 2013).

There is a limited number of studies reviewing the use of technologies in the construction health and safety domain. Among these, Zhou et al. (2013) conducted an extensive literature review of construction safety management for approximately 30 digital technologies. Skibniewski (2014) studied information technology in construction safety. Guo et al. (2017) provided a literature review investigating 15 digital technologies used for construction safety management. Akinlolu et al. (2020) performed a bibliometric analysis analyzing digital technologies in general with the help of VOSViewer software.

Table 1. Previous literature review and bibliometrics studies

Reference	Data Collection (Time range; Database; Number of documents), Data Analysis (Software)	Findings	Differences between previous studies and this review

Zhou et al., 2013	1986 to 2012; Web of Science, Science Direct, Engineering Village, EBSCO Host; 119	Nearly 30 technologies are identified, the most utilized ones being virtual reality, sensor technology, database, 3D and 4D visualization technology, and robotics. 17 research topics are identified and observed in several time spans. While previous studies focused on reactive safety management, recent studies have placed more emphasis on proactive safety management with real time information and visualization technologies. Most of the studies are conducted at the project level. Considering the technologies to enhance health and safety in the construction projects, most of them are at construction phase. In terms of project type, a high portion of studies investigate building projects.	The time range is limited in terms of including recent studies. The number of studies is limited. Bibliometrics software is not used. On the other hand, this study provides a larger time range. Both WoS and Scopus were used in this study. In addition, Bibliometrics software, which provides a wide range of visualization and systemic review options was used in this research. This study further provides a detailed representation of how these technologies can be used with respect to construction phases. This study further presents the analysis of data regarding at least 450 reviews which are summarized in Table 5.
Skibniewski, 2014	2006 to 2014; Web of Science, Scopus; 136	Information technology has been used in evaluating occupational health and safety, monitoring performance of workers, equipment, and construction site, developing robotics to conduct construction work. These are significant for a safe construction environment. RFID, ZigBee, UWN, GPS, WLAN and 3D visualization provided different capabilities to increase safety performance. Three main research areas were sensor-based	The time range is limited in terms of including recent studies. The number of studies is limited. Bibliometrics software is not used. Technologies inspected is limited to information technology. On the other hand, this study does not have a time

		systems, robotics and manipulators and other systems.	limitation. It uses Bibliometrics software, and several technologies are included in the search. Moreover, this study lists the information provided about 450 journals papers in a separate table (Table 5). This study also provides an in-depth and comparative discussion of emerging technologies in terms of construction safety.
B. H. W. Guo et al., 2017	2000 to 2016; Web of Science, Science Direct, Taylor & Francis, ASCE Library, Engineering Village; 111	Digital technologies show a considerable potential in enhancing safety performance by safety planning in design phase, real-time location tracking and warning, and safety knowledge.	The time range is limited in terms of including recent studies. The number of studies is limited. Bibliometrics software is not used. However, this study does not have a time limitation. It uses Bibliometrics software, and several technologies are included in the search. In this study, most recent data is used to provide a search with properly selected search queries.
Subedi and Pradhananga, 2021	2000 to 2017; Google Scholar; NVIVO	Major factors that affect safety of construction workers are categorized as personal (physical, physiological, cognitive, psychological), environmental, and organizational.	The time range covers recent studies; however, years 2018, 2019, 2020 and 2021 are not covered. Only one database is used. Discussion section is limited. This study does not have a time limit as

			restriction, it uses both databases for review (WoS and Scopus). The discussion section of this study is enriched with many resources along with providing directions for future research. In this study, Table 5 provides an in-depth representation of widely used technologies in construction safety.
Akinlolu et al., 2020	2009 to 2019; Scopus; 240; VOSViewer	The UK, USA and China are determined as three leading countries in health and safety construction technologies area. The co-occurrence of keywords analysis results in seven main research areas, namely, project safety design and planning, visualization and image processing, digital technologies for project monitoring, information management and internet of things, automation and robotic systems, health and safety and accident prevention, structure evaluation. Further, five emerging trends are determined.	The time range covers recent studies; however, years 2020 and 2021 are not covered. Only one database is used. Only English-language documents are included. On the other hand, this study covers a very wide time range, reviews papers also published in other languages, and uses more databases. In this study, the technologies are listed in terms of their frequency of use so that practitioners can see which technologies are of utmost importance for construction safety (See Figure 10). Moreover, in this study, a very broad review of mostly used technologies is provided (Table 5).

Even though there are some other studies examining construction technologies used in the construction health and safety (Akinlolu et al., 2020; B. H. W. Guo et al., 2017; Skibniewski, 2014; Zhou et al., 2013), the number of studies conducted research in this area is scarce. These studies are listed along with their data collection and analysis methodology, main findings, and differences between this research and previous similar review are shown in Table 1. The existing studies have some limitations in terms of time range coverage and scope. One major drawback is that most of the existing reviews do not cover recent years in the analysis. Moreover, the existing reviews have a narrow scope in terms of keywords. For example, several studies investigated the use of specific technologies such as BIM (Hire et al., 2022; Akram et al., 2019) and sensing and warning technologies (Antwi-Afari et al., 2019) but a broader array of technologies has not been thoroughly investigated. To fill this gap, this study goes a step further by covering studies investigating a wide range of technologies in construction health and safety up to 2021. In this respect, this study aims to review and analyze the existing literature and to discuss and reveal the characteristics of the previous studies. In this context, the main objectives are:

(1) to identify digital technologies used for construction health and safety

(2) to identify the most frequently used keywords, the most influential publication sources, academics, documents, countries, and institutions

(3) to reveal the relationships of keywords, scholars, and documents with the help of bibliometrics analysis

To achieve the above-mentioned objectives, the study is structured as follows. This study uses a scientific mapping approach by examining existing studies as part of the research methodology that can be seen in section three. The fourth section shows analysis along with results. The fifth section details and discusses the research findings. The last section presents the conclusions of the study.

RESEARCH METHODOLOGY

This study adopts a literature review-based approach to examine and summarize the studies on digital technologies used for occupational health and safety in the construction industry. Since it is a growing and multidisciplinary area, conducting a manual review becomes laborious for some. Besides, manual review tends to be more subjective and error-prone. Bibliometrics is the application of mathematical and statistical methods to investigate the literature quantitatively (Wang et al., 2021). Bibliometric analysis helps to determine the size of studies in a particular scientific field and provides a complete view of the field. It is also useful for researchers, journal editors, and referees as it transforms qualitative data into quantitative data (Baraibar-Diez et al., 2020; Wallin, 2005). Hence, the bibliometric analysis provides more objective and scientific results compared to manual reviews (Wang et al., 2021). Accordingly, in this study, bibliometric analysis was utilized, and bibliometric research steps were conducted based on several studies (Wang et al., 2021; Liang et al., 2020; Aria and Cuccurullo, 2017). The research methodology steps followed in this study can be seen in Figure 1.

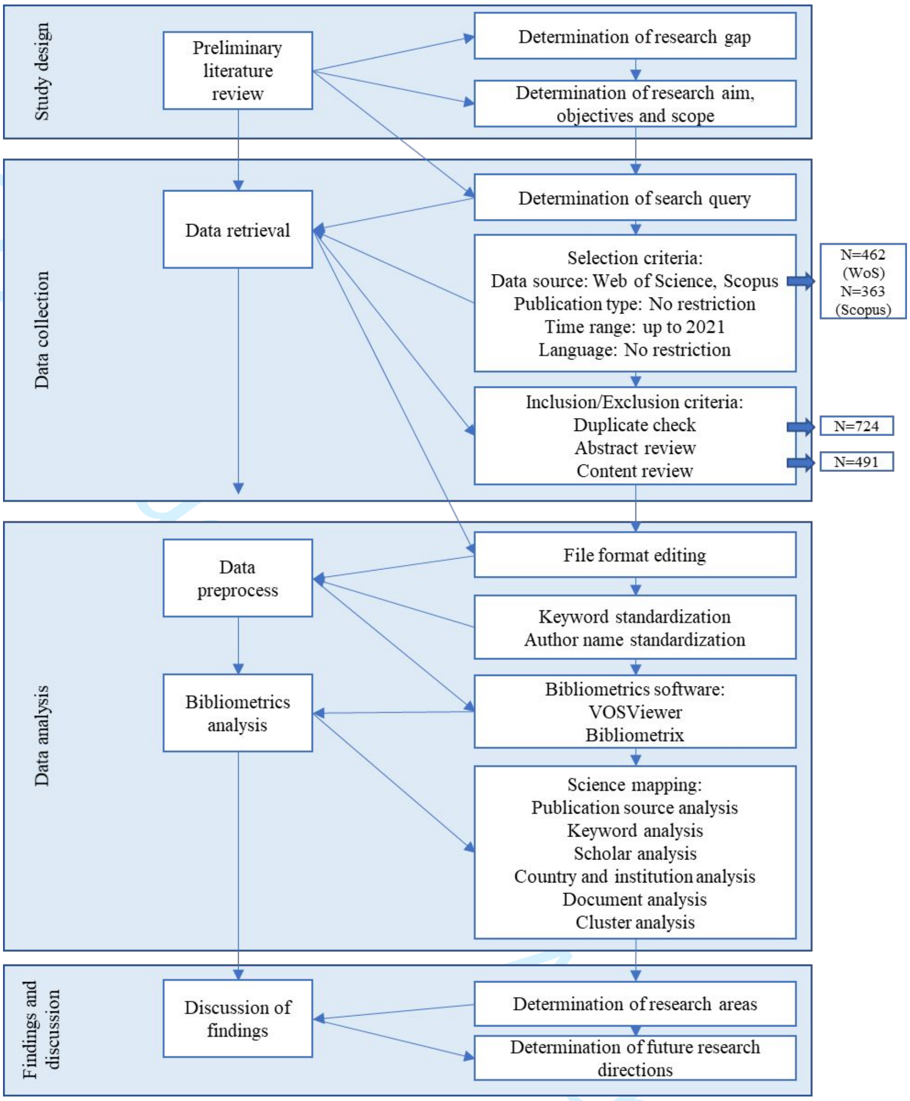

Figure 1. Research Methodology Steps

Initially, conceptual boundaries were established by referring to search terms determined by the purpose of the study. The search query was composed based on a preliminary literature review and existing literature review studies (Boton et al., 2021; Chen et al., 2021; Subedi and Pradhananga, 2021; Akinlolu et al., 2020; Perrier et al., 2020; Wang et al., 2020; B. H. W. Guo et al., 2017; Zhou et al., 2013). The preliminary literature review was utilized to ascertain the coverage of keywords. The search query consisted of three parts: keywords referring to (1) the construction industry, (2) occupational health and safety, and (3) digital technologies. Based on the previous literature review studies, similar terms and synonyms for the construction industry and occupational health and safety were determined. After iterative searching and inspection of obtained results, digital technologies which cover a broad range of techniques were identified by a comprehensive list. The terms related to the help of Boolean operators “AND”, “OR”. In the search query, * wildcard, which represents any number of characters was used to cover different spelling variations and similar words. For instance, “building information model*” was used to refer to building information model, building information modeling, and building information modeling; “sens* tech*” was used to find terms such as sensor technology, sensor technologies, sensing technology, sensing technologies, etc. Similar to study of Zhou et al. (2013), the search query was specified to be searched in publication title, abstract, and/or keywords (which is expressed as TS=() in Web of Science, and TITLE-ABS-KEY() in Scopus). The search query can be seen in Table 2.

Table 2. The search query

("construction industry" OR “construction sector” OR “construction company” OR “construction firm” OR “construction organi*ation” OR “building industry” OR “building sector” OR “building project” OR “civil engineer*”) AND	(1) the construction industry
(“occupational safety” OR "health and safety" OR “safety and health” OR “construction safety” OR “worker safety” OR “labo*r safety” OR “accident”) AND	(2) occupational health and safety
("information technolog*" OR “information and communication technology” OR “digital tech*” OR “digiti*ation” OR “industry 4.0” OR “construction 4.0” OR “construction tech*” OR "automation" OR “computer vision” OR “building automation system” OR “autonomous construction” OR "building information model*" OR “BIM tech*” OR “BIM system” OR “digital twin” OR “virtual twin” OR "robot*" OR “robotic*” OR "simulation" OR “virtual reality” OR “augmented reality” OR “augmented virtual*” OR “immersive media” OR “mixed reality” OR “virtual prototyp*” OR “gam* tech*” OR “serious gam*” OR “internet of thing*” OR “big data” OR “additive manufactur*” OR “digital prefabr*” OR “modulari*ation” OR “modular construction” OR “3D print*” OR “wearable device*” OR “wearable sensing device*” OR “wear* sens*” OR “wearable simulation*” OR “e-hard hat” OR “artificial intelligence” OR “machine learn*” OR “deep learn*” OR “cloud tech*” OR “cloud comput*” OR “blockchain” OR “e-learn*” OR “online teaching” OR “management information system*”OR “building management system” OR “e-safety management system” OR “ultra wideband” OR “ultra-wide band” OR “ultra-wideband” OR “geographic information system*” OR “global position* system*” OR “remote sens*” OR “sens* tech*” OR “sensor” OR “motion sens*” OR “ubiquitous sensor network” OR “wireless tech*” OR “wireless network” OR “wireless local area network” OR “wireless sensor network” OR “WiFi” OR “internet of service*” OR “web service*” OR “automatic identification system*” OR “3D visual* tech*” OR “4D visual* tech*” OR “photogrammetry” OR “image process*” OR “video” OR “camera” OR “vision analysis” OR “virtuali*ation” OR “barcod*” OR “mobile comput*” OR “eye-tracking” OR “eye track*” OR “zigbee” OR “bluetooth” OR “accelerometer” OR “inertial measurement unit” OR “unmanned aerial” OR “drone*” OR “light detection and ranging” OR “laser detection and ranging” OR “laser scan*” OR “3D scan*” OR “point cloud” OR ”radio frequency identification” OR “3D model*” OR “4D model*” OR “real-time” OR “real time”	(3) digital technologies

OR “proximity warning” OR “early warn*” OR “ubiquitous connectivity” OR “ultrasound” OR “ultra sound” OR “infrared” OR “action recognition” OR “object recognition” OR “object identif*” OR “physiological status monitor*” OR “mobile device*” OR “smartphone” OR “industry foundation class” OR “smart build*” OR “smart city” OR “smart factory” OR “cyber physical system” OR “embedded system*” OR “human computer interaction” OR “smart construction object*” OR “personal electronic dosimeter*”)

The first stage of bibliometric research is to determine the data source. Among several data sources, Web of Science (WoS) and Scopus, which are multidisciplinary and selective bibliographic databases are the most reliable and valid ones (Pranckutė, 2021). WoS and Scopus were selected as data sources since they are comprehensive publication and citation databases. Then, the research boundaries were determined. In terms of publication type, the search was not restricted. It was intended to provide a comprehensive outline of the research area. Journal and conference papers convey the research based on theoretical and practical applications. They are published after peer-review and detailed examination; hence, they represent a high-quality research (Wang et al., 2021). Books, book chapters, and reviews cover significant previous cumulative know-how. The inclusion of different types of publications helps to increase the value of the study. The time range of the study was selected as up to 2021 to provide the development of the area from past to present and to represent the most recent studies. According to the bibliometric search, the earliest paper on digital technologies in construction health and safety was published in 1986. Hence, the time range was set from 1986 to 2021. The language of the publications was not restricted to prevent bias caused by the exclusion of studies that were not written in English according to suggestion of Akinlolu et al. (2020). Moreover, there were some other exclusion criteria such as newspapers, editorial materials, and books were not used in the search. All documents with a core subject of safety but not relevant to emerging technologies were left out of the review.

After the determination of selection criteria, the search was conducted on 6th December 2021. It resulted in 462 studies from WoS and 363 studies from the Scopus database. Due to use of two databases, there were duplicate documents that had to be removed (Zhou et al., 2013). In a total of

825 documents, 100 duplicates were detected and removed. To determine whether the documents obtained as a result of the search are within the scope of the study, the titles and abstracts of the documents were reviewed by five authors. If the abstract was not satisfactory, the manuscript was also inspected. The main inclusion criteria were as follows (similar to study of Zhou et al. (2013)): The study should be conducted in the construction industry. The industry covers a broad range of activities such as transportation, bridge, and dam construction, and they were included. The study should emphasize health and safety. Some studies were related to structural health or structural safety of the construction, and they were not included. The study should also emphasize the use of digital technologies. Studies that utilize technologies as the main methodology, show an implementation of them or investigate them conceptually were included. Some methods like analytical network process, analytical hierarchy process, fuzzy logic, system dynamics, structural equation model, etc. were not included since they are mostly statistical analysis methods rather than advanced technologies. After a review of the documents, 491 publications remained on the final list.

One of the most important steps in the bibliometrics analysis is the creation of science maps. Science mapping helps to create visual representation among different factors such as authors, sources, documents, and countries, and to improve the bibliometrics analysis (Moral-Muñoz et al., 2020). Among several related software, VOSViewer and Bibliometrix were employed in this study. This software can create and view bibliometric maps and is capable of using data from WoS and Scopus databases in addition to being freely available. They are advantageous compared to others, VOSViewer provides advanced graphical visualization and Bibliometrix presents a comprehensive group of methods (Moral-Muñoz et al., 2020; van Eck and Waltman, 2010).

Before the analysis, data were preprocessed. The data files were modified to be suitable for bibliometrics software (ris file for VOSViewer and excel file for Bibliometrix). The keywords and author names were standardized to obtain clearer results. Because, in similar articles, the same concepts can be defined with different spelling variations and similar words. For this reason, it is necessary to standardize the keywords before conducting the analysis (Su and Lee, 2010). For example, "building information model", "building information modeling", "building information modelling" and "BIM" referring to the same technology were standardized as "building information model (bim)". After data preprocessing, the final bibliometric files were transferred to VOSViewer and Bibliometrix software. The information obtained from the analysis was visualized and several science maps were created to present an understandable picture of the previous studies on digital technologies used in construction health and safety. The next section details the analysis and results.

ANALYSIS AND RESULTS

According to the results of this review, it was seen that the studies related to digital technologies in construction health and safety have been published since 1986. As digital technologies emerged and enhanced throughout the years, the number of studies increased continuously. Even though there are a few studies in the 1990s, the research area aroused interest in the last 10 years and the number of research studies has an increasing trend as can be seen in Figure 2. The trend of the increase can be said to be parallel with the development and adoption of technologies in the construction industry.

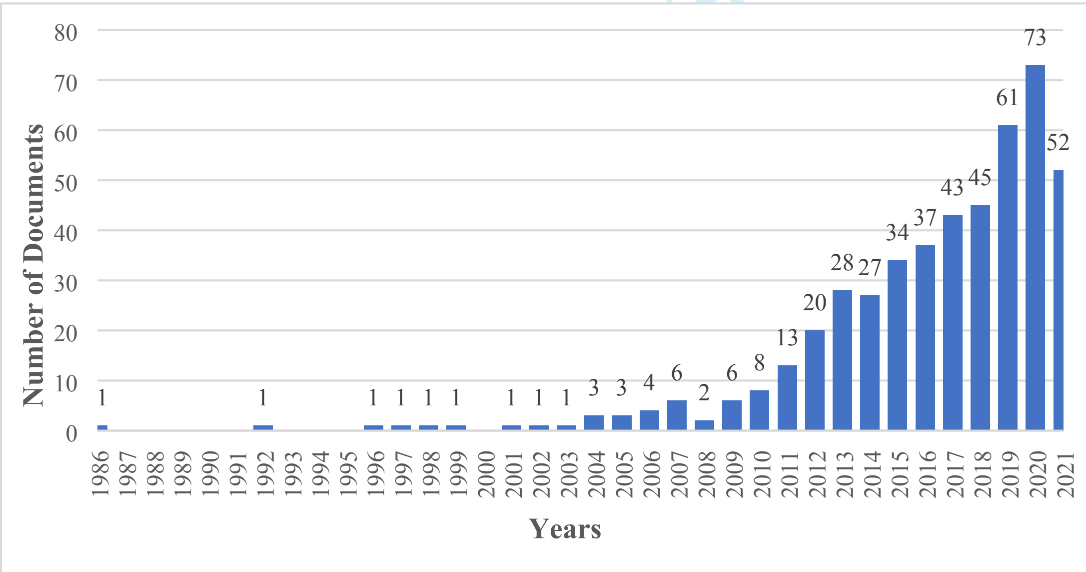

Figure 2. The number of publications by year

In total, 491 documents were included in the bibliometrics analysis. Most of the documents were articles (279), which were followed by conference and proceedings papers (180). Other documents were reviews (28), book chapters (2), editorial material (1), and a short survey (1).

Publication source analysis

In total, 209 publication sources were identified in which the documents were published in the form of journals, books, etc. Most influential sources based on the number of documents published were shown in Figure 3. Considering the source impact based on the number of total citations, the top ten sources were Automation in Construction (1918 total citations), Journal of Construction Engineering and Management (1115), Safety Science (806), Journal of Computing in Civil Engineering (505), Advanced Engineering Informatics (144), International Journal of Injury Control and Safety Promotion (108), Accident Analysis and Prevention (106), Computers & Education (104), International Journal of Project Management (92), Journal of Intelligent & Robotic Systems (89), and International Journal of Construction Management (58).

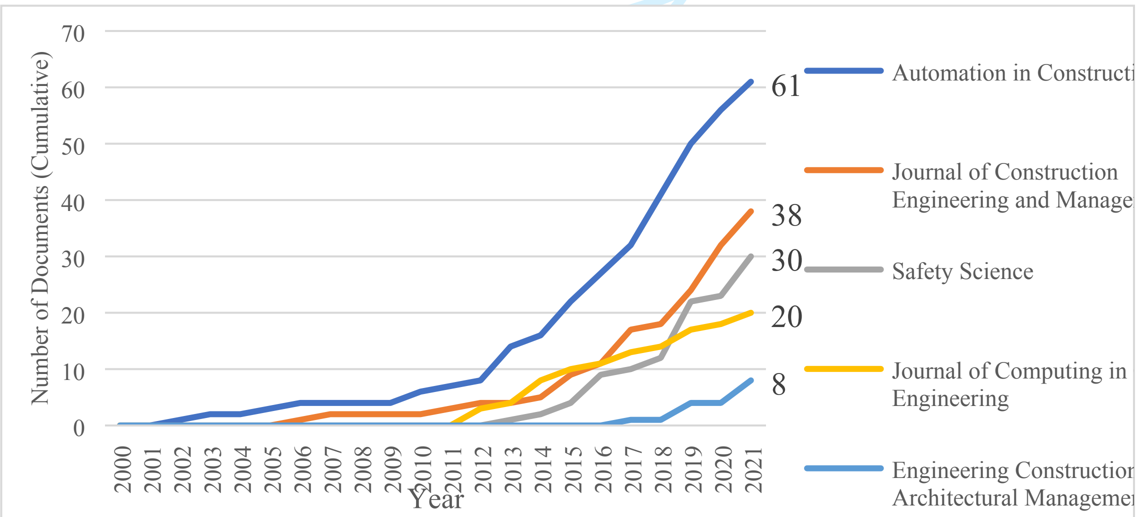

Figure 3. The number of publications by sources

Keyword analysis

Author keywords represent the essence and the focus of the publication. The publications that are conducted on similar topics are expected to have strong relationships. Co-occurrence analysis of keywords shows the relationship of keywords according to the number of documents that appear together. In the visualization, the size of the nodes represents the occurrences of keywords, and the links between keywords represent connections. Label and circle size increase in direct proportion to the occurrence frequency of keywords. The smaller the distance in between, the stronger the relationship between them (van Eck and Waltman, 2010). In the analysis, a total of 2201 keywords were identified. Keywords that appear at least 5 times were selected, and 202 keywords met the threshold. In Figure 4, the keyword co-occurrence map was constructed by using VOSViewer. The most frequently occurring keywords were "health and safety" (149 occurrences), "construction industry" (132), "construction health and safety" (125), "building information model (bim)" (89), "management" (73), "accident prevention" (65). A total of 7 clusters were identified that were represented with different colors.

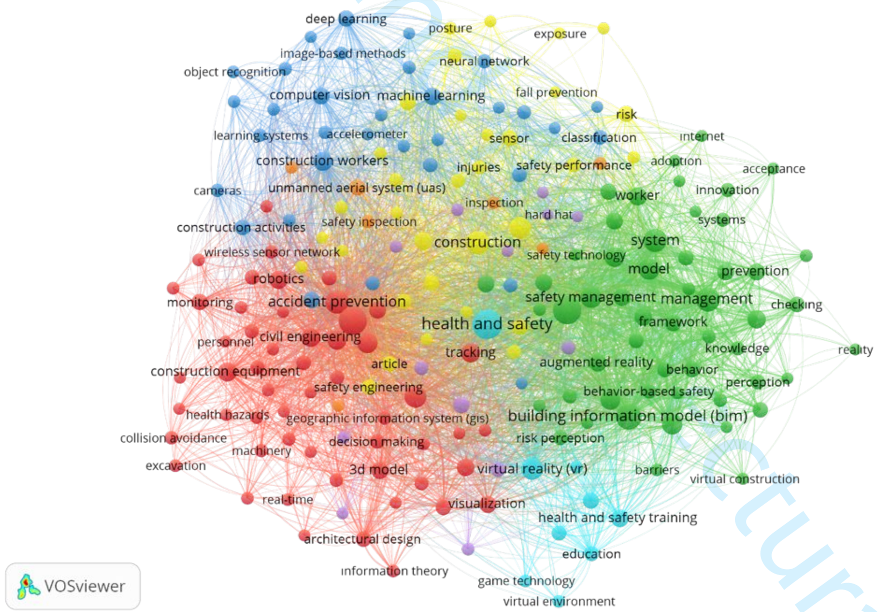

Figure 4. Keywords co-occurrence map

Scholar analysis

In the analysis, 1149 scholars were specified in total. The average number of scholars per document was found as 2.3. The average number of documents per scholar was 0.4. Most of the scholars (1128) studied in collaboration with other scholars and produced multi-authored documents. Only

21 of the scholars produced single-authored documents. This may indicate that the studies on digital technologies in construction health and safety require collaborative efforts. Authors who produced the highest number of documents and had the highest citations were Jochen Teizer, Heng Li, and SangHyun Lee as can be seen in Table 3.

Table 3. Most influential authors based on the number of publications

Author	Number of Publications	Average Publication Year	Total Citations
Jochen Teizer	27	2013	633
Heng Li	24	2017	576
SangHyun Lee	12	2017	308
Chukwuma Nnaji	11	2020	72
Amin Hammad	10	2015	114
SangHyeok Han	10	2015	188
Masoud Gheisari	8	2019	9
Yantao Yu	8	2019	292
JeeWoong Park	8	2019	168
Fei Dai	8	2017	157
Waleed Umer	7	2019	75
Sogand Hasanzadeh	7	2019	141
Xincong Yang	7	2019	107
Alex Albert	7	2018	164
Houtan Jebelli	7	2018	98
Behzad Esmaeili	7	2017	157
Ibukun Awolusi	6	2020	119
Matthew R. Hallowell	6	2018	156
Helen Lingard	6	2017	46
Martin Skitmore	6	2016	187

Scholar's production was also investigated with a figure which was created by Bibliometrix based on the number of documents produced per year and total citations per year (See Figure 5). The size of the nodes represents the number of publications by the author. The color of the nodes shows the total citations per year. According to the figure, it can be said that as a growing area, digital technology use in construction health and safety attracted the attention of scholars, and several authors started to study this topic recently.

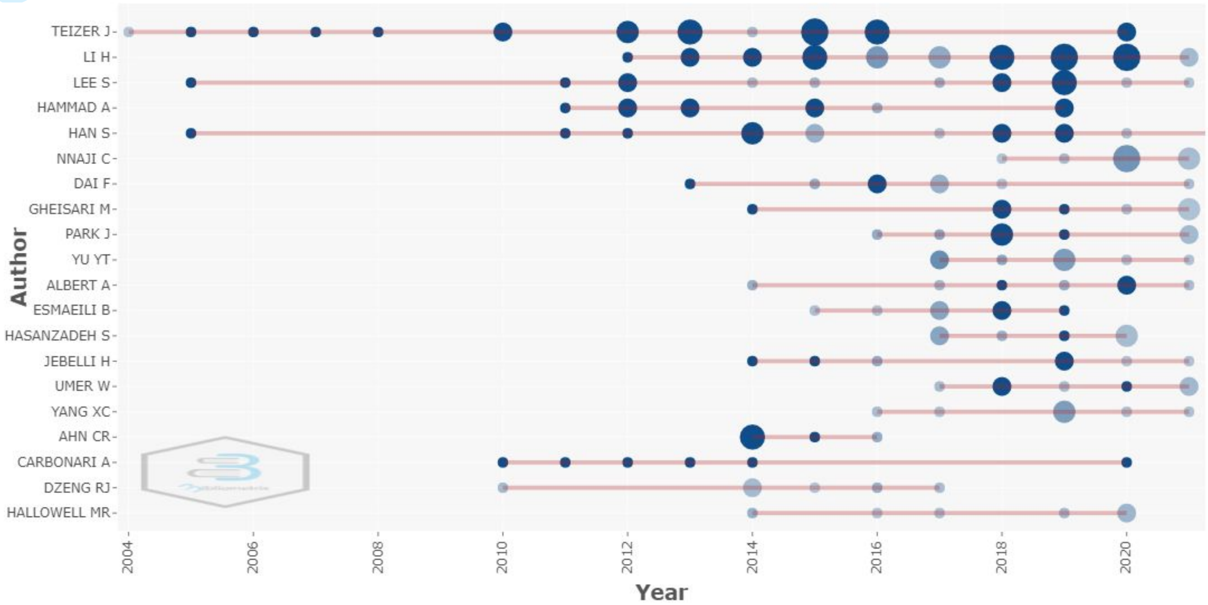

Figure 5. Scholar's production over time

Co-authorship analysis for scholars which helps to show the relations between scholars based on their number of co-authored documents was performed in VOSViewer. The threshold for a minimum number of documents was selected as 1 to include all authors. The minimum cluster size was determined as 2, which helps to show small collaborations between authors as well. Figure 6 shows the co-authorship map of scholars where the size of the nodes represents the number of documents by scholars. It should be noted that only connected authors were shown in the figure for a clearer map. However, there are several other small clusters that are not connected. In the map, 32 clusters were identified. Leading scholars of the first 20 clusters according to the total link strength were Heng Li, Jochen Teizer, Yantao Yu, SangHyun Lee, Waleed Umer, Fei Dai, Chukwuma Nnaji, JeeWoong Park, Houtan Jebelli, Matthew R. Hallowell, Alex Albert, Qiming Li, Masoud Gheisari, Xiangmin Li, Behzad Esmaeili, Hyunsoo Kim, Dong Zhao, Mohamed Al-hussein, Xiaowei Luo, Zainab Riaz.

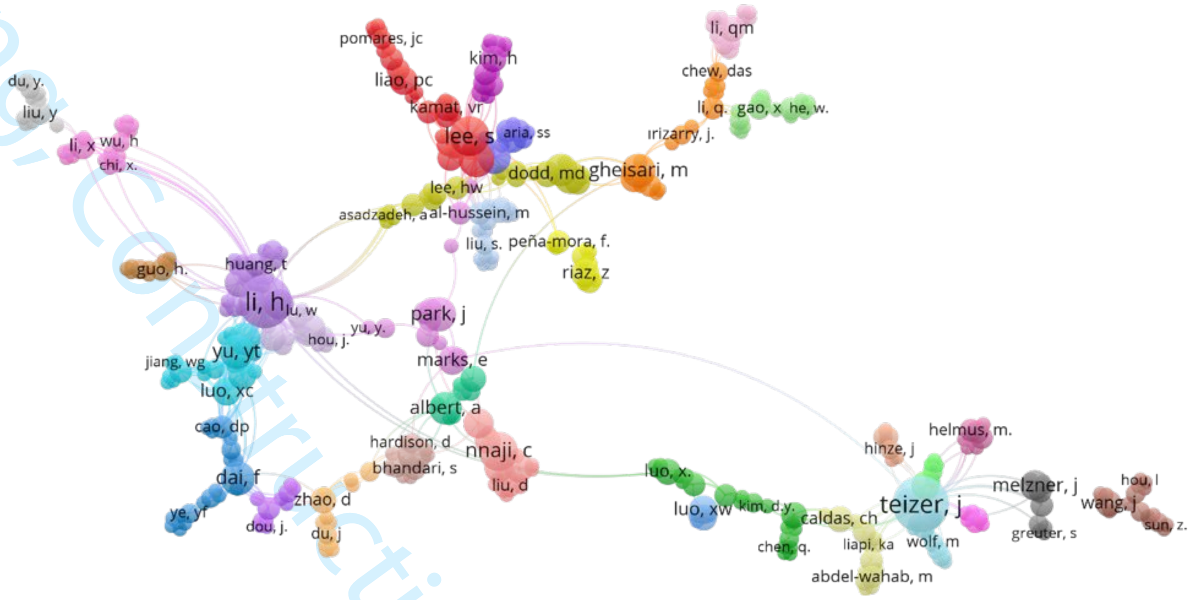

Figure 6. Co-authorship map of scholars

Country and institution analysis

The production of countries and institutions was evaluated based on the corresponding author's affiliation. The findings revealed that the most productive 10 countries were the United States (273 documents), China (182), the United Kingdom (59), Australia (53), South Korea (46), Canada (31), Spain (28), Malaysia (25), Germany (22) and Italy (20). In Figure 7, countries were shown based on the number of publications they produced. Further, the collaborations between countries were also visualized. The color of the countries on the map shows the number of documents produced by scholars from that specific country. The dark blue color represents a high number of documents. The weight of the links shown in red color represents the frequency of collaboration between countries. The most frequent collaborations were between the USA and China (14); and China and Australia (14).

When affiliations of the scholars were inspected, the most relevant institutions were found as Hong Kong Polytechnic University (39 documents), University of Florida (18), Tsinghua University (15), University of Alabama (14), Royal Melbourne Institute of Technology (RMIT) (13), Southeast University (12), Marche Polytechnic University (12), National University of

Singapore (11) and Oregon State University (11) according to a number of documents produced in these institutions.

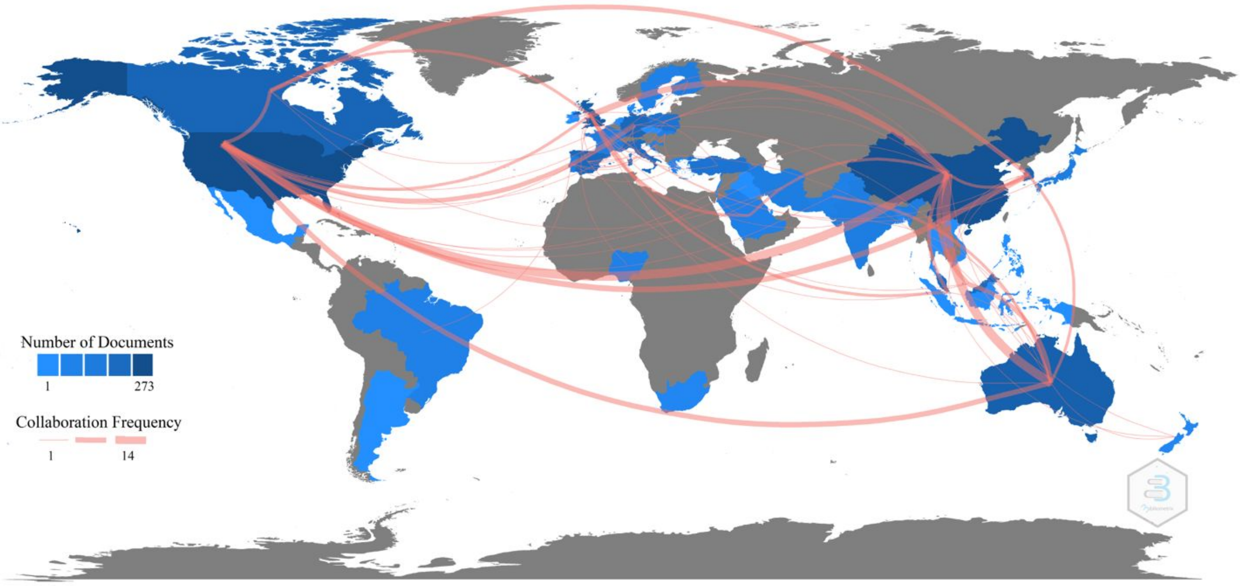

Figure 7. Country production and collaboration map

Document analysis

The most influential papers that affected other studies are important to understanding the development of the research area. The most cited 20 documents were shown in Table 4. Considering that the average number of citations per document was 18.3, these studies were highly influential. Considering total citations per year, the study of Boje et al. (2020) "Towards a semantic Construction Digital Twin: Directions for future research" was an important study with the highest value (35 total citations per year).

Table 4. Most relevant documents based on the number of total citations

Document	Title	Source	Research focus	TC	TC/Y
(Carter and Smith, 2006)	Safety hazard identification on construction projects	J. Constr. Eng. Manage.	Investigates of current levels of hazard identification on three U.K. construction projects.	221	13.8
(Zhang, Sulankivi, et al., 2015)	BIM-based fall hazard identification and prevention in construction safety planning	Saf. Sci.	Investigates how potential fall hazards, which are accidentally built into the construction schedule are identified and eliminated in the early planning phase of a construction project.	175	25.0

(Li, Lu, Hsu, et al., 2015)	Proactive behavior-based safety management for construction safety improvement	Saf. Sci.	Investigates proactive behavior-based safety in terms of improving construction safety. Proactive behavior-based safety is simply referred to behavior-based safety with the technology integration.	148	21.1
(Zhang, Boukamp, et al., 2015)	Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA)	Autom. Cons.	Investigates an ontology based semantic model to organize, reuse, and store construction safety knowledge by formalizing this approach.	145	20.7
(H. Guo et al., 2017)	Visualization technology-based construction safety management: A review	Autom. Cons.	Investigates research and development, implementation methods, achievements and barriers on the use of visualization technology in safety management.	120	24.0
(Awolusi et al., 2018)	Wearable technology for personalized construction safety monitoring and trending: Review of applicable devices	Autom. Cons.	Investigates the applications of wearable technology for personalized safety monitoring. It further focuses on the features of wearable devices and safety metrics to predict safety performance.	115	28.8
(Zou et al., 2017)	A review of risk management through BIM and BIM-related technologies	Saf. Sci.	Investigates the latest efforts in technology toward managing risks such as BIM, automatic rule checking, knowledge-based systems, and reactive and proactive information technology.	104	20.8
(Lee et al., 2012)	RFID-Based Real-Time Locating System for Construction Safety Management	J. Comput. Civ. Eng.	Investigates the development of a real-time locating system for safety management to provide accurate and robust localization performance in construction sites, where signal availability is often times is an obstacle to overcome.	99	9.9
(Cheng et al., 2013)	Data fusion of real-time location sensing and physiological status monitoring for ergonomics analysis of construction workers	J. Comput. Civ. Eng.	Investigates remote monitoring of construction workers in terms of ergonomically safe and unsafe behavior. In this respect, the study uses fusion data of construction workers, who are remotely monitored terms of their location and physiological status.	93	10.3
(Albert et al., 2014)	Enhancing construction hazard recognition with high-fidelity augmented virtuality	J. Constr. Eng. Manage.	Investigates the development of some special hazard recognition strategies such as use of augmented virtual environment and cognitive retrieval mnemonics to evaluate hazard recognition	92	11.5

			competency of construction workers.		
(Bansal, 2011)	Application of geographic information systems in construction safety planning	Int. J. Project Manage.	Investigates the use of geographic information systems, 3D model with its surrounding topography, and schedule for the development of safe execution sequence in terms of identifying hazards in the construction safety planning process.	92	8.4
(Wang et al., 2015)	Risk assessment of work-related musculoskeletal disorders in construction: State-of-the-art review	J. Constr. Eng. Manage.	Investigates the available techniques for work-related musculoskeletal disorders risk assessment listing the benefits and limitations. The study further focuses on the categorizations of current techniques to reveal a systematic review of fundamental utilizations.	91	13.0
(Le et al., 2015)	A social virtual reality based construction safety education system for experiential learning	J. Intell. Rob. Syst.	Investigates the use of an online social VR system framework to provide students an environment, where they can perform role playing, dialogic learning, and social interaction for the construction health and safety education.	89	12.7
(Park et al., 2016)	Performance test of wireless technologies for personnel and equipment proximity sensing in work zones	J. Constr. Eng. Manage.	Investigates a proximity detection and alert system for pedestrian worker safety in roadway work zones using Bluetooth sensing technology.	84	14.0
(Park et al., 2015)	Hardhat-wearing detection for enhancing on-site safety of construction workers	J. Constr. Eng. Manage.	Investigates an automated vision-based method for monitoring the people on construction sites to detect whether they are wearing hardhats.	83	11.9
(Riaz et al., 2014)	CoSMoS: A BIM and wireless sensor based integrated solution for worker safety in confined spaces	Autom. Cons.	Investigates the use of BIM and wireless sensor technology to improve visualization in hazardous work environments.	82	10.3
(Jebelli et al., 2016)	Fall risk analysis of construction workers using inertial measurement units: Validating the usefulness of the postural stability metrics in construction	Saf. Sci.	Investigates the effectiveness of velocity of the bodily center of pressure and the resultant accelerometer to predict the construction workers' fall risk in stationary postures.	80	13.3
(Park et al., 2017)	Framework of automated construction-safety monitoring using cloud-enabled BIM and BLE mobile tracking sensors	J. Constr. Eng. Manage.	Investigates a low-cost automated safety monitoring system to facilitate construction safety monitoring process. In this	78	15.6

			respect, the study presents a safety monitoring system framework in the form of a cloud-based real time on-site application.		
(Goulding et al., 2012)	Construction industry offsite production: A virtual reality interactive training environment prototype	Adv. Eng. Inf.	Investigates a VR interactive training environment to practice new working conditions related to offsite production practices.	78	7.8
(Hadikusumo and Rowlinson, 2002)	Integration of virtually real construction model and design-for-safety-process database	Autom. Cons.	Investigates the visualization of the construction processes to evaluate safety hazards. The study further proposes a design for safety process tool.	75	3.8

Note: Adv. Eng. Inf.: Advanced Engineering Informatics, Autom. Cons.: Automation in Construction, Int. J. Project Manage.: International Journal of Project Management, J. Comput. Civ. Eng.: Journal of Computing in Civil Engineering, J. Constr. Eng. Manage.: Journal of Construction Engineering and Management, J. Intell. Rob. Syst.: Journal of Intelligent and Robotic Systems, Saf. Sci.: Safety Science, TC: Total Citations, TC/Y: Total Citations per Year.

The historiographic map shows the most relevant direct citations between documents chronologically. With the help of Bibliometrics, a historiographic map was plotted to show the citation relation between documents as can be seen in Figure 8. This graph may help to track similar publications throughout the years in terms of direct citations. For example, Hadikusumo and Rowlinson, (2002) was a leading study historically.

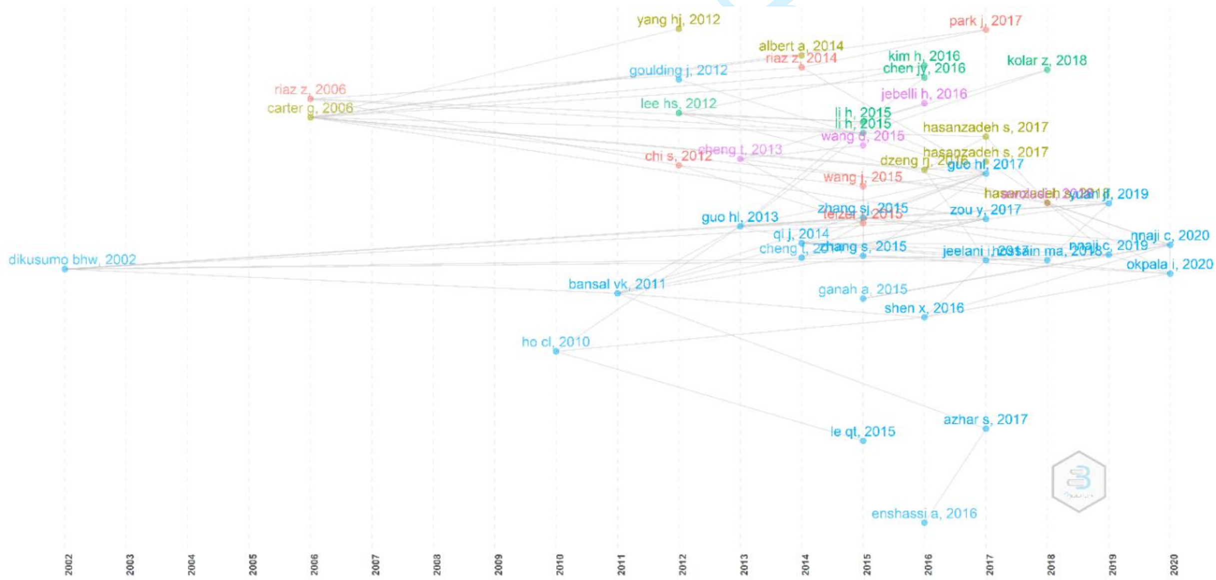

Figure 8. Historiographic map of direct citations

Cluster Analysis

A total of 7 clusters were identified that were represented with different colors. The first cluster included keywords such as “construction industry”, “accident prevention”, “accidents, injuries, and fatalities”, “construction site”, “occupational risks”, and “construction equipment”. This cluster mostly focused on the accident prevention context. In the second cluster, some of the keywords were “construction health and safety”, “building information model (bim)”, “safety management”, “hazard identification”, “design”, “augmented reality”, “visualization technologies”, “internet of things (iot)”, and “eye-tracking”. This cluster mostly included visualization technologies in construction safety. The third cluster covered some words such as “construction workers”, “machine learning”, “computer vision”, “artificial intelligence”, “automation”, and “scaffolding”. In the fourth cluster, some keywords were “construction”, “ergonomics”, “sensor”, “building industry”, “human”, “safety performance”, “prevention through design (ptd)”, and “musculoskeletal disorders”. This cluster was more focused on human-safety relation. The fifth cluster involved “radio frequency identification (rfid)”, “real-time location system (rtls)”, “information communication technology (ict)”. In the sixth cluster, there were “health and safety”, “virtual reality (vr)”, “health and safety training”, “training”, “education”. The seventh cluster involved keywords such as “unmanned aerial system (uas)”, and “digital technologies”. Clusters represent keywords that tend to appear together. Four zones in the thematic map are shown based on the relevance degree (centrality) and development degree (density) of the clusters in Figure 9. Cluster analysis was conducted based on the co-occurrence of author keywords via Bibliometrix. The number of words that were used in the analysis was selected as 230, and the minimum cluster frequency was determined as 5 per thousand documents. Clusters were labeled based on the most frequent 3 keywords in the cluster. Motor themes zone includes co-occurrences that have high centrality and high density, which means that they are well-developed and important themes in the field (Aria et al., 2020). Being shown as Cluster 1 under motor themes, three keywords namely safety, construction, and health and safety were the most frequent words. Cluster 1 being a motor theme, included studies investigating construction health and safety, building information modelling, simulation, visualization, and risk management. Basic themes zone covers co-occurrences with high centrality but low density, which means that they include general topics across different research areas in the field and they are important. Clusters 2, 3, and 4 were positioned under basic themes having relatively high centrality but low density. Cluster 2 included topics such as construction safety, safety training, hazard identification, and eye tracking. Cluster 3 encompassed mainly occupational health and safety, accident prevention, digital technologies, and the internet of things. Cluster 4 mainly focused on occupational health and safety, virtual reality, augmented reality, and training. Cluster 5 came up with keywords such as machine learning, deep learning, computer vision, and ergonomics having moderate density and centrality, and it belongs to both motor and basic themes. Emerging or declining themes indicate low centrality and low density, meaning that they are weakly developed and marginal (Aria et al., 2020). Cluster 6 came up with construction safety management, tracking, and real-time locating as frequent keywords and analyzed under emerging or declining themes. Niche themes show high density but low centrality which means that they are well-developed, but their importance is limited (Aria et al., 2020). Clusters 7, 8, 9, and 10 were revealed under niche themes having high density but low centrality. In these clusters, some common keywords appeared as the construction sector, personal protective equipment, digitalization, and innovation. Cluster 7 enclosed prevention through design and construction equipment in construction health and safety. In cluster 8, radio frequency identification and personal protective equipment keywords were prevalent. Clusters 9 and 10 focused on innovation, and game-based learning, respectively.

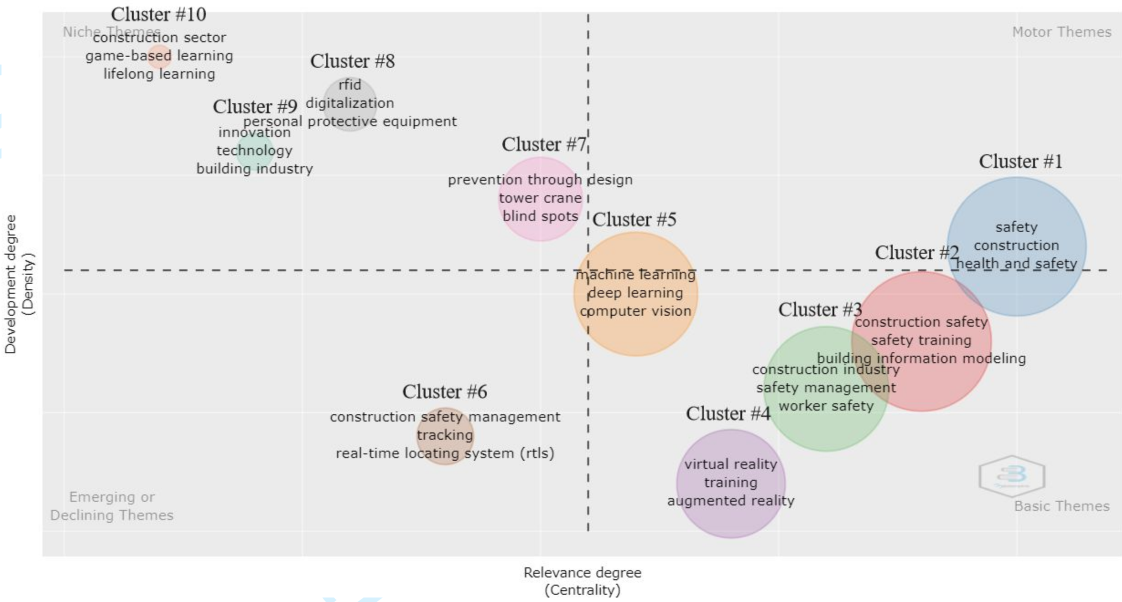

Figure 9. Cluster analysis of author keywords

DISCUSSION

This study conducted a bibliometric analysis of the technology used in construction safety. In this context, interesting findings were reached in terms of the analysis of past studies. In addition to scanning a broad range of papers, the study further revealed the most beneficiary and common technologies used for construction health and safety. The study further discusses the use of these technologies under specific categories.

Digital Technologies used for Construction Health and Safety

Worker safety is one of the most important issues for the sustainability and development of the construction industry (Bhandari et al., 2020). Although each construction accident seems to have different characteristics, detailed studies show that the causes of accidents are common patterns. Identifying these common patterns makes accidents foreseeable and may lead to reducing the number of future accidents (Mohammadi and Tavakolan, 2020).

Unidentified hazards create unmanageable risks. Therefore, hazard identification is an important component in the construction safety management (Carter and Smith, 2006). To identify these risks and protect worker safety in the construction industry, many researchers have benefited from different information technologies as well as BIM, robotics, sensor, and visualization.

Methods such as decision support systems, radiofrequency identification (RFID), Network processes, Optimization, and Geographical information systems (GIS) are just a few of the other information technologies used in the construction industry. In addition, researchers have developed hybrid models by using these technologies together. Awolusi et al. (2022) mentioned the impact of unmanned aerial vehicles and deep learning in construction health and safety monitoring. They implied that the use of such technologies could lead to better decision-making in safety and ability to avoid future accidents.

Investments in research, development, and innovation in the construction industry are generally low (Hinze et al., 2013). Studies on the use of information technologies in construction safety started about 30 years ago. Today, as the number of different safety applications in the construction industry increases, it is observed that the safety performance increases steadily (Hinze et al., 2013). For this purpose, in recent years, many researchers have investigated the use of information technology tools and alerting technologies such as BIM, 4D CAD, GIS, and Virtual Reality (VR) to ensure safety in construction projects (Zhou et al., 2012). According to Zhang et al. (2015), these technologies have become permanent in the construction industry from now on. On the other hand, Nnaji et al. (2020) stated that “More research is needed regarding the adoption of safety technologies in the construction industry.”

IT has positively impacted social communication and real-time knowledge acquisition in the construction industry. However, the sharing of valuable information in the sector is still limited. There is a need for a knowledge base capable of providing real-time information for the entire construction industry (Aguilar and Hewage, 2013). The interoperability of different IT tools can be examined to enable knowledge acquisition in the real-time data collection and processing (Jin et al., 2019).

The below sections explain the digital technologies currently used for construction health and safety and highlight their relevance in terms of construction health and safety practices.

BIM in construction safety

Building information modeling (BIM) has been considered an innovative technology that aims to improve construction projects in terms of safety, efficiency, etc. (Wang and Chong, 2015). BIM enables practitioners to better understand the project and helps reduce the likelihood of accidents (Ganah and John, 2015). BIM helps to reduce the probability of accidents (Ganah and John, 2015) and, thanks to its 3D visualization, also eliminates problems such as lack of foresight in traditional management. Thus, unforeseen hazards in the construction industry can be prevented and "people-oriented" safety management can be created by improving the safety management (Li et al., 2020).

Many researchers in the literature stated that the use of BIM positively affects the safety of construction projects (Park et al., 2017; Kim et al., 2016; Wang et al., 2015; Zhang, Sulankivi, et al., 2015; Qi et al., 2014). In addition, the European Union supports the use of BIM in the development of projects (Cortés-Pérez et al., 2020). Projects that use BIM for visualization save costs while determining the accuracy of their data (Datta et al., 2020). Pham et al. (2020), and Swallow and Zulu (2020) examined the use of 4D-BIM and achieved successful results. While Deng et al. (2019), Mzyece et al. (2019), Y. Li et al., (2020) investigated the use of BIM in safety management, Drozd and Kowalik (2019), Ganah and John (2015), Qi et al. (2014) benefited from BIM for the site and worker safety. In addition, there is a hybrid use of BIM in conjunction with several technologies such as cloud technology (Bennett and Mahdjoubi, 2013), point cloud data and rule checking (Wang et al., 2015), Visual Programming Language (VPL) (Khan et al., 2019), Real-Time Location System (RTLS) (Kim et al., 2016), Indoor Positioning System (IPS)-Inertial Measurement Unit (IMU) (Liu et al., 2020), QR-Code (Lorenzo et al., 2014), BLE Mobile Tracking Sensors (Park et al., 2017), UAV (Alizadehsalehi et al., 2020), safety checking system (Hossain and

Ahmed, 2019; Mihić et al., 2018) in the literature. Previous literature reviews and bibliometrics studies investigated the use of BIM in construction safety. Moreover, there are a lot of studies integrating BIM with other technologies such as wireless sensors, RFID, localization sensors, GPS, GIS, indoor positioning system (IPS) accelerometers, inertial measurement unit, UAV, VR, AR, and cloud data. BIM and UAV are integrated mostly in two ways according to review of Chen et al., (2019). UAVs are utilized for data collection and BIM is used for construction site visualization and identification of construction safety issues. Moreover, BIM can present potential safety hazard locations and the UAV can be used for detection and monitoring. For example, in the study of Liu et al., (2020) indoor positioning systems (IPS) and inertial measurement units (IMU) are integrated with BIM. The system included construction workers' position, walking speed, and facing direction. It showed a significant potential for safety control and monitoring.

However, the implementation of BIM in safety plans and construction safety management is still insufficient (Rodrigues et al., 2021). The main reason for this is insufficient training and lack of wide-ranging use (Enshassi et al., 2016). Malomane et al. (2022) implied that there are critical challenges preventing the implementation of emerging technologies in the construction industry. The most important threats to implementation were shown as a lack of adequate skills and training. The reason behind the low adoption of BIM is further explained as a lack of governmental mandates for BIM use. For example, Hire et al. (2022) mentioned that BIM is still in the early stages of implementation in the Indian construction industry. However, they mentioned that there is great potential for using BIM to adopt it for better safety management. The study further implied that the USA, China, UK are leading countries in BIM use, and they are early adopters of BIM.

Simulations and visualization in construction safety

Construction projects differ from each other with their unique structures. It is therefore difficult to identify all possible safety risks and hazards (Azhar, 2017). According to Rubaiyat et al. (2016), innovative methods should be developed to automatically monitor worker safety at the construction site. In recent years, the use of technologies such as 4D simulations and visualization has increased in construction projects. According to Azhar, (2017) these technologies can provide enhanced safety by allowing project managers to visually assess site conditions and hazards. Projects that use BIM for visualization save costs while determining the accuracy of their data (Datta et al., 2020).

Researchers have investigated the use of simulation in construction safety management and training and obtained successful results. Several studies have explored the use of visualization in the safety of construction projects (Bhandari et al., 2020; Eiris et al., 2020; Lee et al., 2020; Azhar, 2017; Hallowell et al., 2016; Siddula et al., 2016; Li, Lu, Chan, et al., 2015; Le et al., 2014; Tsai, 2014; AlBahnassi and Hammad, 2012). Besides, the use of visualizations in safety training was investigated by some studies (Bhandari et al., 2019; Peña and Ragan, 2017). Bhandari and Hallowell, (2017) proposed a multimedia learning simulation-based training program called naturalistic injury simulation (NIS). The simulation shows the cause and effect of hand injuries with a realistic human hand replica in different scenarios. The study found that workers experienced negative emotions which may help to better perception of risks.

Sensors and wireless technologies in construction safety

The rapid development of motion sensors provides the opportunity to be used in areas such as monitoring worker behavior for safety and worker health in construction, automatically detecting unsafe actions of workers, and receiving feedback. Thus, sensor technology reduces the number of unsafe actions and prevents possible accidents (Han et al., 2014). However, according to Teizer and Cheng, (2015) site safety monitoring in the construction industry is not automatic. Usually, these monitoring are done and evaluated manually (Teizer and Cheng, 2015). For this reason, several researchers have worked on the development of sensor technologies for occupational safety in the construction industry (Hasanzadeh et al., 2020; Lee et al., 2020; Hwang and Lee, 2017; Teizer and Cheng, 2015; Riaz et al., 2014).

Awolusi et al. (2020) identified success factors of wearable sensing devices for construction health and safety monitoring as testability, useful features and qualified employees. Although there is a lot of research on wearable sensing devices (WSD) for personal use, the information is limited in the construction industry (Awolusi et al., 2020). J. Chen et al. (2016) and Wang et al. (2017) developed a wearable electroencephalography (EEG) system. J. Chen et al. (2016) inspected inattentional blindness which is a failure to recognize unexpected hazards due to mental workload of workers during complicated construction tasks. They measured neural signals with EEG and assessed hazards with neural time-frequency analysis. The study further proposed the development of a wearable EEG safety helmet to estimate construction safety. Wang et al. (2017) proposed a wireless and wearable electroencephalography (EEG) system to evaluate the attention level of construction workers by measuring human brain signals. The results indicated that EEG signals can be used to predict the perceived risk level of construction workers. Guo et al. (2017) showed that physical data obtained with wearable devices can be used to detect the psychological state of construction workers. They conducted a study to examine the relationship between the physical and psychological status of workers. They employed wearable devices to collect physical data and questionnaire survey to collect psychological data. The findings implied that physical data is available to measure workers' psychological status. Accordingly, unsafe behaviors can be identified and investigated.

Jebelli et al., (2016) investigated the fall-risk of construction workers. They used inertial measurement unit to collect stability metrics data and compared with the postural stability observed. They implied that collected data helped to predict fall risk of construction workers. Fardhosseini et al., (2020) collected gait pattern data of construction workers using accelerometer embedded in smartphone. Based on the data, they developed supervised-learning algorithms to predict physical fatigue of workers in different working conditions. Tsai (2014) emphasized the risk of fall accidents among engineering students participating in field surveying. The study utilized accelerometer to track behavior of students and image-recognition system for surveillance. The use of these technologies helped promoting safety in education and training.

Zhang and Liao (2020) analyzed the brain activity of participants during hazard recognition with wearable near-infrared spectroscopy (NIRS) system to investigate the influence variables. They proposed and tested site familiarity, safety knowledge, and risk tolerance as the predictors of the change in the brain. Hasanzadeh and Garza (2020) collected data using real-time location tracking sensors, physiological sensor, survey, and interviews to study workers' risk-taking behavior. They found that higher risk tolerance level increases the likelihood of being involved in risky activities and taking risks. Ding et al., (2020) proposed a solution for safety in tunnel construction by developing an intelligent early warning system and a wearable device. They implemented the proposed system in multiple tunnels and produced good safety visualization and monitoring.

Wireless remote sensing technologies provide the real-time location of workers, equipment and materials (Skibniewski, 2014). RFID sensors help collect real-time information and inform construction workers in case of potential risks (Skibniewski, 2014). Li et al., (2015) identified a proactive construction management system for training of precast installation workers. The system builds a training environment using real time location technology and data visualization technology to monitor workers, equipment, and material, give real-time feedback and visualization. Zhang et al., (2020) developed an intelligent safety helmet by using RFID technology and wireless communication, considering ergonomics. Intelligent safety helmet provides attendance and location of the on-site workers, updated information and in-time communication.

Several studies used an eye-tracking system to ensure construction safety (Han et al., 2020; Hasanzadeh et al., 2017, 2018; Dzeng et al., 2016). In the study of Hasanzadeh et al. (2017), eye-tracking technology was utilized, and eye movements of construction workers were recorded. The results suggest that safety knowledge enhances hazard recognition and visual search strategy, and more experienced workers require less time to detect hazards. Jeelani et al., (2017) developed a personalized training strategy including visual cues, feedback on hazard recognition, feedback on visual attention based on eye-tracking data, and metacognitive stimulations. According to empirical findings, the proposed strategy helped to improve hazard recognition levels of construction workers.

Robotic in construction safety

Construction industry requires working in dangerous environments which creates unfavorable conditions for construction workers (Skibniewski, 2014). Hence, robotic technologies are attracting attention as an effective solution for ensuring safety in the construction industry (Kim et al., 2020). Some studies investigated the usability of robotic systems in eliminating different risks that threaten worker health and safety in the construction industry. Bai (2007) developed a robotic bridge painting system. Kurien et al. (2018) developed two systems that will allow off-site workers to remotely connect to the Robotic Construction Worker (RCW). D. Kim et al. (2020) developed a model that aims to predict the proximity between mobile objects to prevent accidents that may occur due to the use of robotics. Jiang et al., (2021) proposed a complete smart construction site based on cyber physical systems and applying it in practice.

Virtual reality, Augmented reality and Mixed Reality in construction safety

Guray and Kismet (2022) researched the use of VR-AR technologies on construction management research and revealed the growing interest toward the use of these technologies. VR, AR and MR technologies are mostly utilized for construction safety training and education. Dawood et al., (2012) proposed merging virtual training environments with 4D or 5D planning and visualization tools for transfer of knowledge and collaborative work in design and construction considering health and safety planning. In the study of Olorunfemi et al., (2018) mixed reality technology was used to enhance communication related to safety risks and hazards. The results showed the performance and feasibility of MR for better safety management. Shi et al., (2018) utilized a multi-user virtual reality system to investigate the effect of social influence on workers' safety behaviors in hazardous conditions. It was found that social influence plays a significant role in safety behaviors.

Unmanned aerial vehicles (UAV)

UAV systems can be used in construction safety improvement by monitoring activities of boom vehicles and cranes on the construction site and monitoring unprotected openings (Ghesairi and Esmaili, 2019). On the other hand, UAV systems have some challenges in liability and legal concerns and safety issues (Ghesairi and Esmaili, 2019).

Artificial Intelligence and Machine Learning

Mansoor et al., (2020) developed a conceptual framework for mobile cranes to improve safety. They utilized a camera which records a video that is interpreted with a mathematical algorithm and is transcribed into commands. This procedure increases the efficiency and safety of the crane operation by eliminating the communication between the signalman and the operator.

Figure 10 provides the frequency of use of emerging technologies in terms of construction safety in past studies. The data provided indicates that sensors and wireless technologies are the most commonly implemented technologies in terms of promoting safer practices. Moreover, the figure proves that AI, ML, BIM, and DT are other important technologies in construction safety. Especially, when used together, the technologies are even more effective as implied in previous studies. Table 5 summarizes the areas of digital technologies used in construction health and safety studies. This information is expected to direct construction practitioners to select the appropriate digital technology according to their needs.

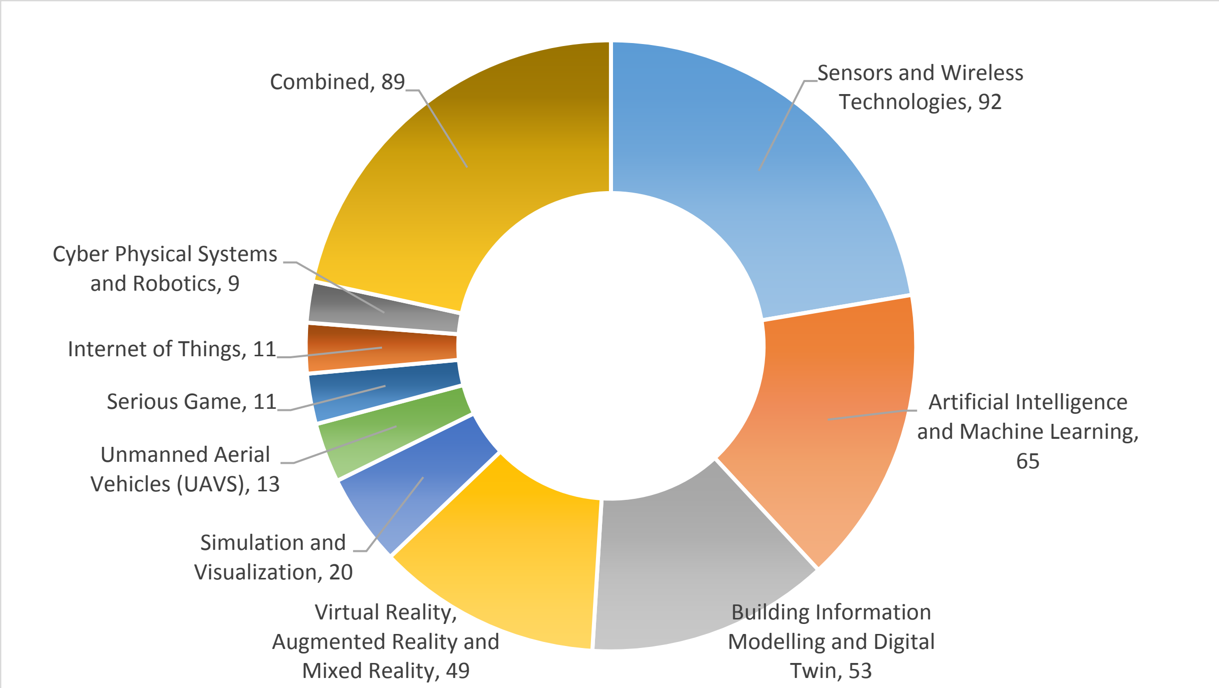

Figure 10. The Frequency of Digital Technology Use in Construction Health and Safety Studies

Table 5. Relevant areas of digital technologies used in the construction health and safety

Digital Technology	**Use in the construction health and safety**
Building information modelling (BIM)	- Identification (hazard identification, risk register system) - Planning (safety planning) - Design (prevention through design) - Training and education - Prevention (risk prevention) - Analysis (safety risk assessment, object-oriented and process-oriented job hazard analysis) - Visualization (near-miss information visualization) - Simulation (safety risk simulation) - Monitoring (automated safety checking system, safety risk reviews, safety audit, automated safety rule checking) - Management (construction safety management, occupational hazard management)
Artificial intelligence (AI) and Machine learning (ML)	- Identification (workers, safety hazards and accidents, safety risks, safety leading indicators, personal protective equipment, spatial safety risk identification of earthmoving and surface mining activities), - Classification (safety accidents, accident causes, scaffolding, construction site photos for roof detection) - Detection (real-time worker safety detection, safety characteristics, workers' actions, real-time hardhat wearing, non-certified work, safety guardrail) - Prediction (health and safety risk, safety hazards and accidents, safety outcome, post-accident disability status of workers, severity prediction models of falling risk for workers at height) - Measurement (safety performance on roof sites, dynamic blind spots for construction equipment operators) - Prevention (occupational injuries, collisions between heavy equipment vehicles and other on-site objects) - Analysis (predictive safety risk analysis, safety status of construction workers, level of collision safety, risk factors for work-related musculoskeletal disorders, physical fatigue, posture analysis, ergonomic assessment, behavior-based safety, causality patterns of unsafe behavior leading to fall hazards) - Monitoring (safety surveillance, hardhat wearing, early-warning system for site work in hot and humid environments) - Real-time occupational health and safety management system

Virtual Reality, Augmented Reality and Mixed Reality	- Training and education (construction safety training for construction workers, safety education for engineering students) - Identification (hazard identification, hazard recognition) - Planning (safety planning for construction activities performed at high elevation) - Visualization (visualization of danger factors) - Simulation (safety system and simulation) - Communication (safety risk communication, safety culture integration)
Sensors and Wireless Technologies	- Identification (hazard identification and recognition, construction activity recognition, automated action recognition, workers' unsafe behaviors) - Detection (hazards, hard hat wearing, detection of fall portents, detection of near-miss accidents and falls, collision detection, obstacle detection) - Classification (classification of unsafe actions) - Measurement (construction workers' physical demands, physical fatigue, construction worker's musculoskeletal disorder risks, visual attention and situation awareness, inattentional blindness, psychological status, attitude estimation and stability measurement of articulated heavy vehicles in the construction industry) - Prevention (proactive accident prevention, prevention of struck-by-falling-object accidents, collision avoidance) - Analysis (safety risk, workers' behaviour analysis) - Visualization (real time tracking and visualization of resources) - Simulation (wearable simulations) - Monitoring (health and safety monitoring, ergonomic analysis, worker movements, hazardous area intrusion, environmental monitoring on construction sites, exposure to solar uv radiation, proximity warnings of construction safety hazards, autonomous crane safety monitoring, workers and scaffolds monitoring) - Management (construction worker safety management system)
Simulation and Visualization	- Design and planning of a healthy construction workplace - Detection (hazard detection) - Safety training - Visualization (visibility and proximity based risk map of earthwork site - Simulation (earthmoving projects, near real-time motion planning and simulation of cranes in construction) - Analysis (ergonomic job analysis for workplace design, job hazard area identification) - Modelling - Monitoring (on-site safety monitoring and warnings

Future Recommendations

This study provides a future direction for researchers to categorize and focus on the niche themes of construction safety technology. In this respect, Figure 10 was created to categorize these technologies concerning construction project phases. For example, BIM and visualization were identified as the key technologies for prevention through design. Moreover, VR, AR, serious games, and eye tracking were determined as the most influential technologies for training and education. For the equipment during the construction phase, GIS, GPS, and robotics were implied as the essential themes that one needs to focus on when integrating technology into equipment. Finally, it was proposed that simulation, visualization, and VR are critical for safety monitoring in the operational phases.

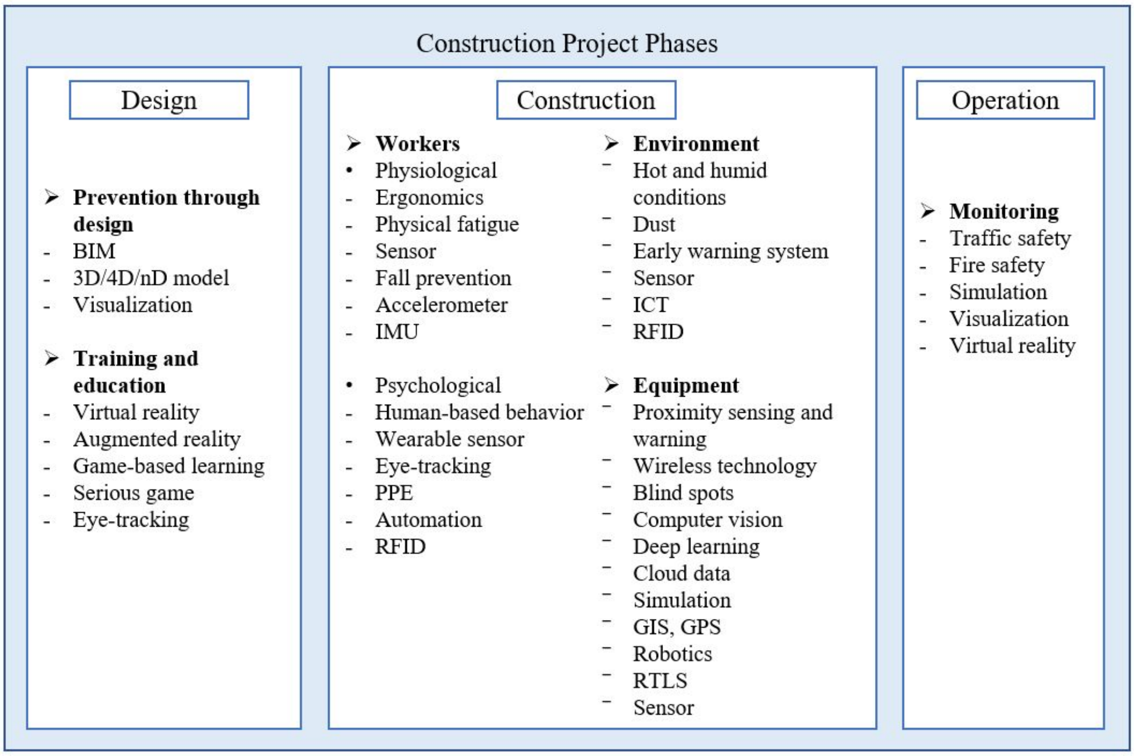

Figure 11. Emerging Safety Technologies based on Construction Project Phases

CONCLUSIONS

The bibliometric analysis includes evaluations regarding publication sources, scholars, keywords, and documents aimed to identify key issues related to the use of digital technologies in construction health and safety and provide a research framework. This study investigated the use of digital technologies in construction health and safety. In this respect, a broad range of studies was scanned. This study provides a comprehensive analysis including all available studies without restricting document type, publication year, and language. Further, two bibliometric software was utilized to better visualize the existing studies.

When conducting the study, some challenges were encountered. Especially, data exchange between two different software (WoS and Scopus) was a significant challenge to generate the bibliometrics analysis. Moreover, new research is on the way for similar topics, which led researchers to conduct a timely analysis and proper investigation of past studies. Studies that were published in a different language were another challenge to overcome since the researchers aimed to include all studies for the specified period of the bibliometrics search. Finally, the keywords used were carefully selected since some keywords were very specific to finding target research. Several keywords were scanned through to best represent the focus of the study. Hence, future research on similar topics shall consider the importance of using the proper keywords to come up with a more reliable analysis. This study provides directions for researchers to (1) find the proper sources for bibliometrics analysis (2) search databases with proper keywords, and (3) generate a systemic review for the emerging technologies in safety. Hence, the study encourages researchers to better visualize the data regarding past studies and the impact of those as well as leading industry practitioners to consider what influential technologies can be used to improve safety performance.

Although information technology in construction safety has been one of the popular topics among researchers in the last decade, the study revealed that there are still research gaps in this field. The analysis indicated that there is still a growing need for promoting artificial intelligence methods in terms of construction safety. The study further showed that a human-oriented safety management system should be established to best address safety concerns. Real-time knowledge acquisition was also detected as a lacking item in most construction projects. The detailed analysis of past studies further implied that there is a growing need for digitalization in construction safety along with promoting personal protective equipment. This study recommends that prevention guides for construction accidents must be in place to protect construction workers from being injured. Moreover, the establishment of application guides for countries that will adopt BIM shall be put in place. Another recommendation is to design studies that combine multidisciplinary areas. The use of digital technologies in construction health and safety covers several disciplines. The field of computer science and information technology is necessary for the development and implementation of digital technologies. On the other hand, medicine and healthcare are required to inspect the health and safety of construction workers. Besides, the field of law, legal and forensic issues deal with judicial processes related to accidents and hazards.

On the other hand, the study had some limitations such as the use of subjective procedures in the title and abstract review and keyword standardization and selection of thresholds which may result in older keywords and underrepresentation of novel areas.

Despite certain challenges, this study has considerable implications for researchers, industry practitioners, and policymakers. First and foremost, this study points out a very important topic, which is the safety of construction workers. Considering the impact of work-related hazards and accidents upon society, this study has the potential to help construction people to develop new safety measures and 'stop the line' when necessary. This is because this study provides the most trending and frequently used technologies of which the effectiveness has already been proven. Workers can benefit from the finding of this research to benefit from the technologies when working in hazardous conditions. The risk processes can be replaced with automated processes. This in turn could reverse several fatal cases and protect many who would find themselves in hazardous situations. Second, the study encourages researchers to conduct a similar search with more recent data, where the proven benefits of technology integration in safety processes are apparent. This way, construction researchers could focus on the niche themes and develop research accordingly to best favor the use of technologies in safety research. Industry practitioners may further benefit from the findings to revise and revisit their safety programs. They could potentially develop a 'zero mistake' policy at work, which could save many lives using such emerging technology trends as VR, AR, BIM, and so on. Finally, policymakers could develop new strategies to improve safety programs with the smooth and transparent integration of technology into processes with the proven benefits of technologies used in previous implementations. Since this study provides a very broad analysis of how these technologies are of use in construction, construction managers can draw future directions regarding their use.

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