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Review

Exploring the role of building information modeling in construction safety through science mapping

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ABSTRACT

Deplorable safety management practices are damaging the reputation of construction sector. Though legislation has specified rules and regulations for safety improvement, the state of violation is still alarming. Its root causes are unavailability of information and lack of integration of core data with other project activities. The technology that can help in overcoming these issues is the need of hour. Building Information Modeling (BIM) has the potential to address poor safety performance which inspired many researchers to explore its application for safety improvement throughout project lifecycle. The primary objective of this study is to review and analyze the literature on BIM. For this purpose, comprehensive bibliometric and scientometric analyses were performed using science mapping tools on the articles published during the period 2000–2018 using selected search string. The analyses on 97 articles majorly resulted in the identification of BIM application characteristics, construction safety application domains and their relationship. The relationship in the form of a factor-feature matrix shows the association strengths between various safety factors and BIM features, revealing interesting findings. It is found that visualization is the most promising feature of BIM while hazard identification is a highly significant application domain of construction safety. The findings drive the knowledge areas available for future research endeavors in BIM and safety. Taking the lead, app developers can design and develop a dedicated BIM plugin to plan and monitor safety in construction projects.

1. Introduction

The Architecture, Engineering, Construction and Operations (AECO) is an influential industry due to its socio-economic significance and contribution to gross domestic product (Farooqui et al., 2008). However, higher accident statistics of AECO industry are not only damaging its reputation but also posing a challenge to future innovation (Zou et al., 2017). Despite a significant improvement in safety enforcement due to appropriate legislation such as Occupational Safety and Health Act (OSHA) in the USA, National Institute for Occupational Health (NIOH) in India, Health and Safety Executive (HSE) in UK and Labor Department in Hong Kong, the socio-economic impact of injury and fatality rates is still alarming (Li et al., 2015; Tixier et al., 2017). In the workplace comparison of European statistics over the period 2008–2016, AECO industry represents the highest number of fatalities (Eurostat, 2016). Globally, the fatality rate in construction industry has increased from 15% to 19% during the last five years (Bureau of Labor Statistics, 2016). To reinforce it further, some authors reported accident rates in the range of 24–30% (Ganah and John, 2015; Li et al., 2015; Sunindijo and Zou, 2011). The contributing factors behind these alarming figures are dynamic workplace, worker's behavior, lack of coordination and inadequacy with risk management to name a few (Enshassi et al., 2016; Gibb et al., 2006). These excessive figures demand to deploy technology, resources and finances for bringing down

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the casualty rates rather than just pointing out the reasons. It can be done by changing the mindset of construction workforce and engraving safety in every task (Li et al., 2015) as safety is the essential key for successful outcome of any project (Zhang et al., 2011). And it is not unstoppable; Han et al. (2009) found that construction accidents can be prevented by providing effective safety management.

Safety management includes many factors such as legislation (Tam et al., 2004), planning (Biagini et al., 2016; K. Kim et al., 2016; Kim and Teizer, 2014), training (Clevenger et al., 2015; Park and Kim, 2013), monitoring (Park et al., 2016), cost (Li et al., 2015) and many others. Among all, safety planning is a fundamental step and includes identification of potential hazards along with their preventive measures (Chantawit et al., 2005). However, current practices of project management do not consider safety planning as part of the overall planning for project execution (Getuli et al., 2017; Zhang et al., 2011). Due to a fragile link between safety planning and work task execution, safety personnel face difficulties like unavailability of information and lack of integration of available data with project activities, ultimately resulting into hazardous worksite conditions (Zhang et al., 2013). A majority of construction accidents are neither reported nor documented except for those which gain public or media attention. Thus without appropriate information, it is difficult to perform operative safety planning (Raheem and Issa, 2016). Likewise, Zahoor et al. (2016) reported that most of the contractors do not pay sufficient consideration to safety manuals and some of them even do not prepare such manuals. In contrast to this, Masood et al. (2012) found that according to managers, accidents are reported and recorded thoroughly but workers do not agree with this opinion. Also, a poor exchange of communication between workers and administration is reported in the literature (Emmitt and Gorse, 2009) and in that, the increasing number of migrant and illiterate workers cause more communication problems (Han et al., 2009). Similarly, Zhang et al. (2015b) concluded that safety communication is a challenging task under the dynamic and rigorous jobsite conditions. In view of all the existing problems, the AECO industry needs to improve inadequacies of existing manual practices so that safety targets can be attained (Zhang et al., 2013).

In this regard, it is desirable to have such a technology which may assist in analyzing and communicating safety issues for improving overall performance (Han et al., 2009). Various candidate technologies such as remote inspection through photogrammetry and unmanned aerial vehicles (UAVs), sensing devices like radio-frequency identification (RFID), global positioning system (GPS) and laser scanning have been developed to facilitate safety management (Lu et al., 2011; Teizer, 2015). Their core advantages lie in objectivity, ease of access, reliability of data and cost-effectiveness. Of various features provided by these and other candidate technologies, visualization is an extremely promising and appropriate tool for effective safety management because of the advantages such as exchange of information and ideas between different stakeholders (Bouchlaghem et al., 2005). Motiboi and Abdullah (2017) concluded that animation, an application of visualization, is the most effective method for safety understanding. A person's ability to hypothesize and understand abstract concepts can be enhanced with the help of visualization. Clevenger et al. (2015) found that building information modeling (BIM), through a graphical representation of physical and functional properties of a service, helps in explaining the concepts using 3D visualizations. Not only it manages visuals, BIM also contains information that can help in generating drawings, design and energy analysis reports, facility management and other assessments that can help in better decision-making (Ding et al., 2014; Ganah and John, 2015; Zhang et al., 2015b). BIM can be used during the lifecycle of a project as a shared source of information about any facility (Antwi-Afari et al., 2018; Cho et al., 2014). It provides enhanced collaboration and coordination between project stakeholders (Abbasnejad and Moud, 2013; Ahmad et al., 2018; Enshassi et al., 2016). Azhar (2017) found that BIM can be utilized for better construction safety by developing close link of safety issues with construction planning, and can provide comprehensive site layout and safety plans to facilitate safety communication. Ahmad et al. (2018) found that BIM has a positive trade off in project risk and can be considered as an active risk management system.

Numerous studies have reported various aspects of BIM. State-of-the-art in research has focused on assessing critical factors of BIM implementation (Antwi-Afari et al., 2018), mapping its global research (Zhao, 2017) and exploring collaboration in BIM based construction networks (Oraee et al., 2017). While some reviews are focused on integration of particular aspects of management with BIM such as sustainability (Chong et al., 2017) and risk management (Zou et al., 2017), very few studies comprehensively review the application of BIM features in the area of safety management. Xiaer et al. (2016) and Ku and Mills (2010) studied design for safety (DfS) tools and explored the relationship of BIM with DfS. Their findings conclude that BIM has a potential to achieve DfS. Additionally, Martínez-Aires et al. (2018) have recently carried out a synthesis of BIM based literature on construction safety management. It is a very interesting review which uses manual techniques to synthesize the relevant body of literature. Similarly, Mohammadi et al. (2018) and Swuste et al. (2012) have also carried out systematic manual reviews in the area of safety management research. However, Markoulli et al. (2017) axiomatized that traditional manual reviews focus on some trees but fail to provide an overview of the whole forest – pointing to a lack of holism. Thus, the entire exercise makes such reviews more subjective and run a risk of introducing bias. To improve upon such limitations, Jin et al. (2019) reviewed construction safety literature through science mapping tools, despite the focus not being particularly on BIM and its safety management features. However, science mapping has certain inherent limitations such as lack of critical synthesis, less supportive databases, possibility of technical inaccuracy and expert opinions. Therefore, this study incorporates a comprehensive overview using science mapping as well as a critical synthesis of previous literature in an attempt to achieve the best of both worlds. This is justified since previous studies loosely explain the relationship of application domains of BIM in construction safety but a thorough review using science mapping tools on BIM and construction safety is missing in the literature. Such a synthesis will not only help provide the much needed automation to construction safety but also pave a way for aggressive adoption of BIM due to its undiscovered strength in safety implementation. Therefore, this study investigates the correlation between BIM and safety, and identifies their key attributes. The literature search was conducted using keywords and a search string was developed using Boolean operators. Further, informetric analysis containing bibliometric and scientometric techniques has been performed on the extracted literature. With the help of science mapping tools, various aspects of literature are probed. Based on this, trends in research are highlighted and gaps for future research have been explored. The novelty of this study is in its potential to stimulate the body of knowledge towards producing quality theories and tools to enhance construction safety using BIM.

2. Research methodology

To ascertain the current research on the state of BIM and construction safety management, a comprehensive literature review has been carried out in four phases with flowchart shown in Fig. 1 and description given below.

The phase-1 included the identification of relevant academic journals and associated databases. This was done using different search engines such as Elsevier, Scopus, ASCE library, Google Scholar, Web of Science (WoS) and others. The search period was fixed between the years 2000–2018. Boolean operators AND and OR were used to formalize keyword search. The search string used was ((“Building information modelling” OR “BIM”) AND (“construction safety” OR “safety management” OR “safety”) AND (“construction”)). The search explored the title, abstract and keywords which were sufficient to identify and

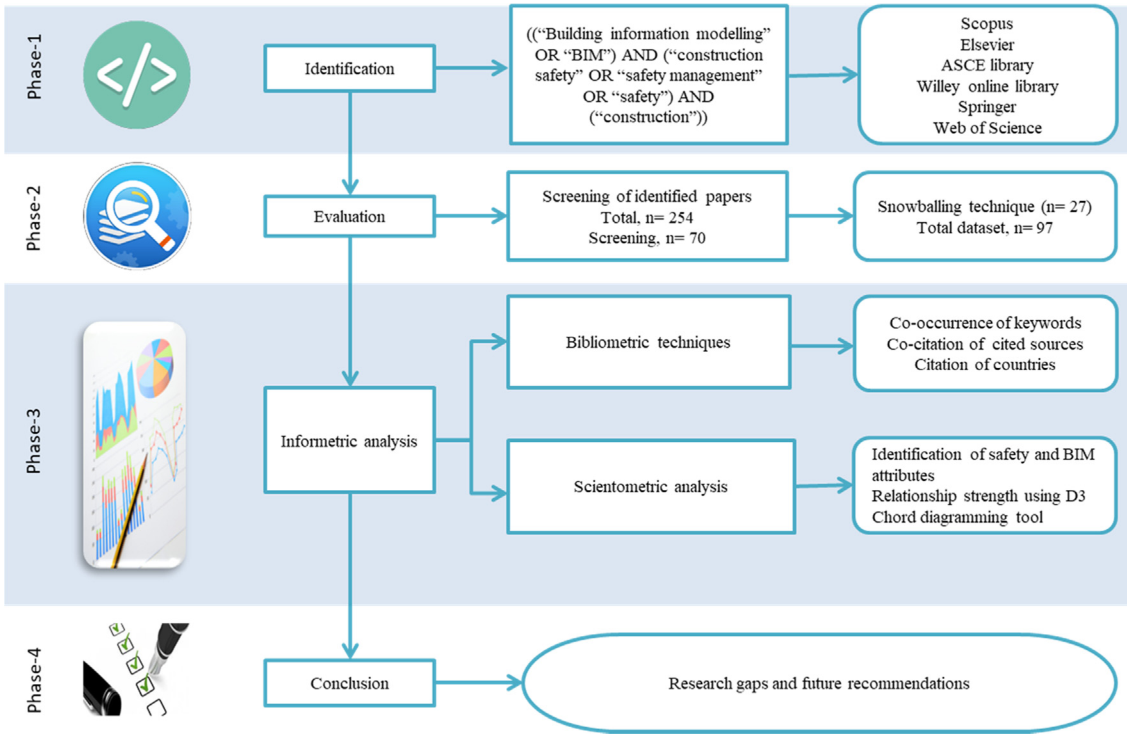


Fig. 1. Flowchart of research methodology.

extract the relevant articles. The selection criterion of journals was based on previous studies of similar nature to encompass only those journals which have at least 2 published articles for the relevant period of study (Antwi-Afari et al., 2018; Darko and Chan, 2016; Martínez-Aires et al., 2018). A total of 254 documents including journal and conference papers, and books were extracted as a result of this exercise.

The phase-2 of this study involved the evaluation of identified articles. To enhance the quality of review, only peer-reviewed articles were selected for further analysis, and conference papers and books were omitted. This is due to the reason that journal articles provide more accurate and valued information due to their rigorous review process, and most of the similar studies in the field of construction and project management have included only the journal articles (Zhao, 2017; Zheng et al., 2016). Also, the criterion of minimum 2 papers from the same journal was enforced to ensure a consistent focus of the outlet on construction safety and BIM because in absence of this, several such papers could have been included which were one-offs and did not represent such a consistency. Following the above criterion and removing duplicates, another round of screening of documents was conducted by a thorough review of abstract to identify the articles relevant only to construction safety, resulting into 70 journal articles for further analysis. These articles represented the major journals which report research in this particular area. However, to cover all the relevant publications outside these journals, snowballing technique was applied as suggested by Tixier et al. (2017) and Oraee et al. (2017). Snowballing operates on chain-referral principle where existing study subjects indicate future subjects based on their citation. Thus, the sample grows like a rolling snowball (Goodman, 1961). This technique has already been applied in previous review articles (Oraee et al., 2017; Schanes et al., 2018; Stingl and Geraldi, 2017; Zahoor et al., 2016). In the current review, this step helped to add pertinent literature outside the principal construction engineering and management journals and check citations for the identified articles on the similar criteria to include only the relevant articles. This resulted into addition of 27 papers from different journals, making the total number of papers 97 which were used for the final analysis.

The phase-3 mainly included informetric analysis which is defined as the study related to quantitative aspects of information and it contains bibliometric and scientometric techniques (Hood and Wilson, 2001). Additionally, informetric analysis also contains webometrics which is the study of the quantitative aspects of information resources available on the web based on bibliometric and scientometric approaches (Björneborn and Ingwersen, 2004). Thus, in a way the current review comprises of webometric analysis of the relevant material published online but keeping in view the generally used terminology in the field of construction and civil engineering, this analysis is called informetric analysis.

Bibliometric technique encompasses the scientific mapping and visualization of dataset in an information domain (Van Eck and Waltman, 2010). It incorporates the analysis of publications and their respective properties (de Rezende et al., 2018). On the other hand, scientometric analysis deals with the quantitative aspects of science (Zhao, 2017). The two kinds of analyses are separated by their focus. Bibliometrics is a mathematical view of the metadata of publications, such as details of authorship including institutional and regional affiliations, publication sources and timelines, etc. On the other hand, scientometrics is a quantitative assessment of the content of publications where the science is synthesized to observe trends and behaviors (Zhao, 2017). In this research, science mapping is used for visualizing the physical aspects of scientific research. It also helps in bibliometric analysis for describing the scientific domains and the structure of their respective disciplines. Numerous tools are available for such a visualization which include CiteSpace, VOSviewer, BibExcel, Science of Science tool (Cobo et al., 2011), Gephi and others (Bastian et al., 2009). Special features and shortcomings of various software were studied which led to selection of VOSviewer and Gephi whose features are shown in Table 1.

VOSviewer is a freely available visualization tool for configuring and observing bibliometric maps (Van Eck and Waltman, 2010). Alternatively, Gephi is used for network analysis and graphical representation, and can give more precise networks and graphs (Bastian et al., 2009). It is important to note that data for bibliometric analyses was retrieved from WoS for the identified articles because the selected science mapping tools analyze the articles only in the text format (.txt) files. Due to this, the science mapping (WoS) and scientometric analyses

Table 1
Features of selected science mapping tools.

Tools	Network mapping	Networks analysis	User friendly	Availability	Normalization
VOSviewer	✓	✗	✓	Open source	Association strength
Gephi	✓	✓	✓	Open source	Centrality

(Elsevier, Scopus, ASCE library, Google Scholar, WoS) are performed using different databases. Such that for science mapping, all 70 articles sourced through WoS are included and the additional 27 articles sourced through snowballing could not be included in the bibliometric analysis due to absence of their .txt files on WoS. However, all articles have been technically scrutinized for extracting the science of papers. In doing so, three types of bibliometric analyses were performed in this research: 1) co-occurrence of keywords, 2) co-citation of cited sources and 3) citation of countries. Such analyses have been applied in previous studies (Hosseini et al., 2018; Oraee et al., 2017; Zhao, 2017). Though for this review these analyses have been grouped as bibliometric techniques following the studies of Liu and Mei (2016) and Li et al. (2017), there are reviews which view co-occurrence and co-citation analyses as scientometric investigations (He et al., 2017; Hosseini et al., 2018; Yalcinkaya and Singh, 2015). Also, there are other bibliometric techniques such as burst analysis (which gives insight on the relative changes of significance between keywords over time to highlight research trends), cluster analysis (which indicates research patterns), social network analysis (which investigates social structures by using networks and graph theory), co-authorship analysis (which underlines the scientific collaboration) and institutional contribution analysis (which highlights the scientific contribution). All these analyses explore useful information and provide basis for further research, development and networking. These analyses are not used in the current review owing to a major focus on scientometric analysis.

The scientometric analysis helped identify BIM features and safety management factors through an inclusive content analysis. Using these attributes, a relationship matrix was developed in the form of D3 chord diagram with hover which is a graphical representation of correlation between data in a matrix and is coded in JavaScript. The attributes are arranged symmetrically around a circle by means of a relationship between the data points (Jalali, 2016). The circular layout of this diagram simply illustrates information with large number of attributes, making demonstration of relationship relatively easy (Gu et al., 2014). Further, to give a clear understanding of highly focused phases, articles were distributed into the lifecycle phases under the scientometric analysis. The observation of these analyses resulted into research findings based on which appropriate recommendations are given to help expand future research endeavors.

3. Results and discussion

The phases 1 and 2 of the study, as illustrated in Fig. 1, include the identification and screening of articles. The retrieved articles were further reviewed and analyzed. To avoid any bias and limitation of the manual review, quantified systematic techniques using software platforms were used to explore the body of literature (He et al., 2017; Yalcinkaya and Singh, 2015).

3.1. Co-occurrence of keywords

Keywords depict the fundamental content of articles and clearly demonstrate the range of knowledge areas within a particular domain (Su and Lee, 2010). Following the adopted methodology the extracted papers were imported to VOSviewer to generate a network of keywords. The related keywords convey precise picture of the knowledge domain with its relationship and pattern (van Eck and Waltman, 2014). WoS provides two type of keywords; one is author keywords which are used by authors in the respective papers and the other is keywords plus which are extracted from the title of cited references in the selected dataset. The keywords plus precis highlights new research themes not usually identified from the authors keywords So to operationalize a network of co-occurrence of author keywords was formed initially as suggested by Lee and Su (2010). Normalization using fractional counting was performed for analysis of publications as recommended by van Eck and Waltman (2014). As a result VOSviewer created a co-occurrence map based on the bibliographic data obtained from WoS. It is important to note that due to the inherent limitation of science mapping tools the co-occurrence of keywords is analyzed for publications sourced through WoS only.

In the result, the distance between the nodes depicts the level of proximity between them while the font size shows the level of concentration on that particular aspect (Oraee et al., 2017; van Eck and Waltman, 2014). While creating this map, a criterion was set that only those keywords will be included which co-occur for a minimum of 2 times. Following this, 29 keywords met this minimum level of co-occurrence. The criterion of number of keywords co-occurring has a significant implication for findings; a lower number would result into several insignificant keywords and a higher number would result into very few keywords hindering any meaningful analysis.

In order to simplify the results and harmonize various linguistic regimes, similar terms such as ‘building information modelling’, ‘building information model’, ‘BIM’, ‘building information modelling (BIM)’ were merged into a single keyword ‘building information modeling’. Thus, the network shown in Fig. 2 was developed, highlighting the main research areas in the field of construction safety and BIM. Despite merging BIM related keywords, safety related keywords were not merged due to the fact that either used as an acronym or not, all BIM related keywords refer to the same concept. But safety related keywords may mean different things specially when used as ‘safety management’ or ‘construction safety’. However, keywords of ‘safety’ and ‘construction safety’ may be treated equally since papers only pertaining to construction were included in this review.

In the visualization of network, weights were based on the strength of links while scores were calculated on average normalized citations. The font size shows the number of occurrences for a specific keyword; the larger font size represents the most influential terms. Thus, it can be seen that the most recurring keyword was ‘building information modeling’ followed by ‘construction safety’, ‘safety management’, ‘cloud computing’, ‘prevention through design’, ‘scheduling’ and ‘rule checking’. It is important to note that these are author keywords and as the study is also based on a fixed search string, the largest occurring keywords would evidently be BIM and construction safety. Therefore, it was found necessary to generate co-occurrence of keywords plus network, shown in Fig. 3, to highlight the emerging research areas other than mentioned in author’s keywords which resulted into 50 keywords.

The published literature through co-occurrence of keywords highlights a strong relationship between BIM and construction safety. Several studies have identified the strengths (Choudhry and Zahoor, 2016), barriers (Loosemore and Andonakis, 2007) and project implications (Rechenthin, 2004) of adopting BIM for safety related matters. It has been hypothesized that visualization can significantly reduce the risk of accident (Azhar, 2017). Making matters interesting, it is argued that automated rule-based checking can eliminate human limitations in safety management (Hongling et al., 2016) and improve the construction sites (Enshassi et al., 2016). Also, it helps in monitoring

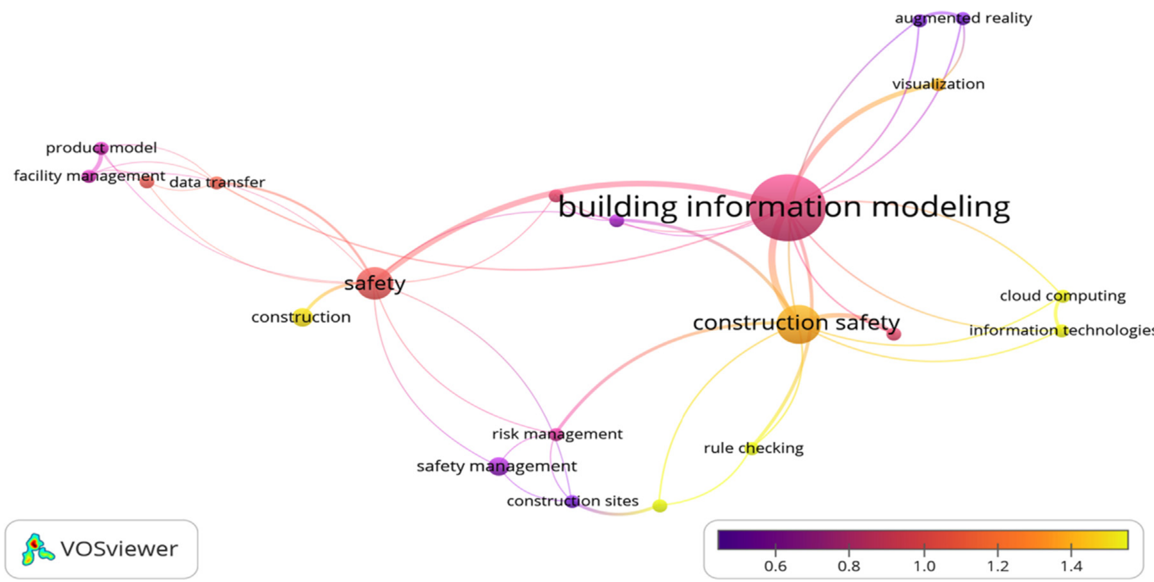


Fig. 2. Co-occurrence network of author keywords.

the performance of building without modification in its design (Zhang et al., 2013; Zhou et al., 2013). It is interesting to observe in the keywords plus network that the most occurring words in the title of cited articles are 'system', 'management', 'construction', 'design', 'model' and 'technology' which are rather generic and give a perception of integration and utility at a holistic level. But there are some keywords similar to those of author keywords such as 'location tracking', 'hazard identification', 'BIM', 'augmented reality', 'simulation'. It can be seen in Fig. 3 that 'safety management' has a link with 'augmented reality', 'design', 'systems', 'checking' and similar other keywords.

Furthermore, it is sufficiently established that most of the accidents in AECO industry are due to schedule overlapping (Moon et al., 2014a) since the traditional approaches of scheduling lack in utilizing 3D tools and do not take into account the uniform resource distribution (Chau et al., 2004; Dawood, 2010; Dawood and Mallasi, 2006). Lack of proper scheduling creates ineffective workspace management and conflicts between different activities and constructability issues which result into chaotic site conditions (Moon et al., 2014b; Zhang and Hu, 2011). Existing planning techniques like Gantt chart, critical path method (CPM) and network diagrams are considered ineffective for detecting schedule conflicts, and it requires new tools to analyze, detect, monitor and control conflicts in workspace (Dawood and Mallasi, 2006). Therefore,

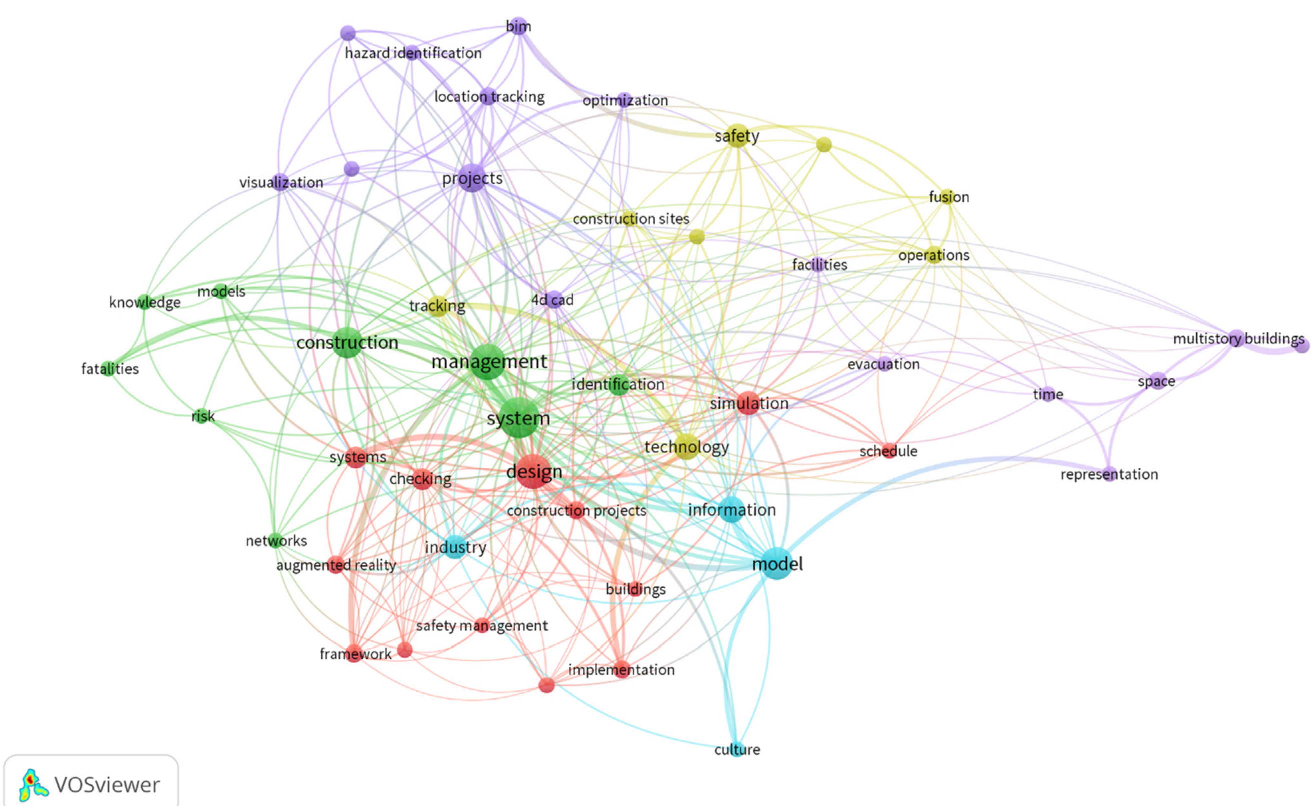


Fig. 3. Co-occurrence network of keywords plus.

scheduling and planning with the help of BIM is an attentive area of research (Moon et al., 2014b). Based on this motivation, Zhou et al. (2013) developed a prototype in which safety is integrated with the detailed information model and scheduling of construction site activities. They concluded that visualization of real-time safety status helps in recognition and elimination of risks during the whole project lifecycle which ultimately leads to an improved safety management. The strong linkage of BIM and safety is showing its importance while safety has no weighted link with emerging areas like cloud computing. It shows that less research has been conducted in these knowledge areas.

3.2. Co-citation of cited sources

Co-citation analysis of sources categorizes the most prominent journals in this research area. The identification of key journals may add value to the researchers for working in the field of construction safety and BIM, and it can also help authors in publication matters (Hosseini et al., 2018). The co-citation of sources is actually analyzed through co-citation of documents published in these sources. As a result, a network was created using VOSviewer for co-citation analysis which gives the weighted degree of cited documents. Again, fractional counting was deployed in creating a bibliographic map. The minimum threshold for citation of sources was set to 6, thus 28 out of 1055 sources met the requirements. The generated map was imported into Gephi for improved visualization and better quality in line with suggestion of Cobo et al. (2011) who highlighted the effectiveness of collaborative working.

Fruchterman and Reingold algorithm was applied for generating a high quality and comprehensive network as shown in Fig. 4. This algorithm has the ability to centralize the highly rated sources by the virtue of gravity feature (Cherven, 2015). Similar terms were merged together and generic terms such as ‘thesis’ and ‘lecture notes’ were excluded. Thus, a network consisting of 20 nodes and 169 edges or connections was formed, highlighting the main journals in the field of safety and technological applications in construction sector. The size of nodes demonstrates the highly cited sources while the thickness of links highlights the strength of association between them. The varying colour intensity demonstrates the strength of links according to the number of citations. The sources with thick edges and dark coloured links represent a high level of collaboration such as Automation in Construction has a strong link with Journal of Computing in Civil Engineering, Safety Science and Advanced Engineering Informatics.

Table 2
Degree centrality and weighted degree of sources.

Sr. #	Sources	Weighted Degree	Degree
1	Automation in Construction	154.7359	19
2	Journal of Computing in Civil Engineering	59.3578	19
3	Safety Science	46.7284	19
4	Advanced Engineering Informatics	44.6746	18
5	International Journal of Project Management	19.9094	20
6	Journal of Construction Engineering and Management	17.7699	22
7	Visualization in Engineering	16.7519	18
8	Journal of Safety Research	16.7345	18
9	Journal of Information Technology in Construction	15.7426	22
10	Computer-Aided Civil and Infrastructure	11.4124	17
11	Construction Management Economics	9.7888	15
12	Journal of Management in Engineering	7.3748	17
13	Construction Innovation	6.1385	15
14	Engineering, Construction &Architecture Management	5.9688	16
15	Professional Safety	5.6757	8
16	Building and Environment	5.4036	17
17	Procedia Engineering	5.3023	17
18	Journal of Civil Engineering and Management	5.1391	18
19	Fire Safety Journal	4.8961	10
20	Building Information Modeling	4.5343	13

It can be seen that the emphasis of highly weighted journals is on technologies. The focused research areas for Automation in Construction are computer-aided design and engineering, facility management, graphics and robotics (Automation in Construction, 2018) while Journal of Computing in Civil Engineering is dealing with database-management systems, computer-aided design systems, remote sensing and bar coding (Computing in Civil Engineering, 2018). The scope of these journals is greatly dependent upon the use of information technologies in construction. However, Advanced Engineering Informatics and Safety Science are not only discussing technological applications but also focus on engineering informatics and techniques of control and management of safety respectively (Advanced Engineering Informatics, 2018; Safety Science, 2018). While Fire Safety Journal has a low citation because the scope of this journal is limited to fire safety design, its management and investigation (Fire Safety Journal, 2018). Professional Safety has relatively a less influenced node as it mainly

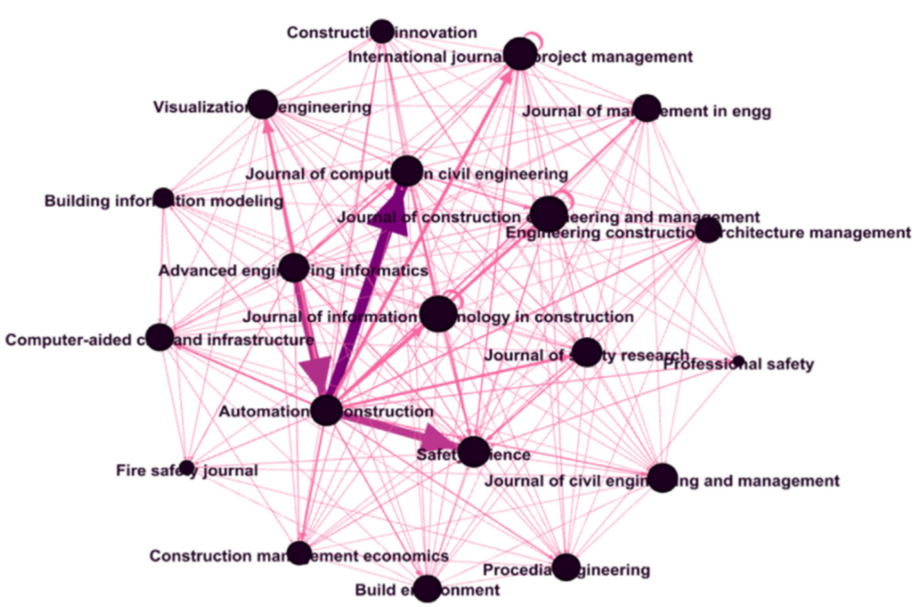


Fig. 4. Co-citation of cited sources.

deals with the hazards identification and protection strategies, and safety investment education. However the role of technological application in this journal is limited (Professional Safety, 2018).

Table 2 shows the degree and weighted degree centrality of sources showing the same results. Degree centrality of a node helps in finding the influence of edges present on a particular node (Kapoor et al., 2013). Weighted degree centrality, also known as strength of nodes, is the sum of all links present on a node in a network (Antoniou and Tsompa, 2008). The relative importance of the sources can be calculated based on weighted degree rankings. Weighted degree centrality of Automation in Construction is the highest, illustrating its higher contribution in the publications and co-citations of this knowledge area, while journal of Building Information Modeling has the lowest value which depicts its impact and relative influence. Therefore, the researchers who are planning to explore this knowledge area are encouraged to focus more towards Automation in Construction, Journal of Computing in Civil Engineering and Safety Science due to their highest degree value. Similarly, these journals may also benefit from this synthesis by attracting researchers in this area through special issues and other editorial support.

3.3. Citation of countries

After analyzing the journals, the network of countries was developed using VOSviewer to explore the countries contributing in the field of construction safety and BIM. This was done to objectively identify where BIM and safety related research and development is centered. Such information is not created to belittle countries with lesser contribution but it is extracted only to guide potential researchers, solution providers as well as solution seekers to converge towards such centers of excellence. To achieve this, the same configuration was adopted as recommended by van Eck and Waltman (2014). A network was developed with 19 sources, showing the link strength of citations. This network was then imported to Gephi for a better output and to modify source names where required, such as 'people of china' was modified to 'China'. Gephi incorporates only those nodes in which link strength is present, therefore some of the sources like Canada, France, Italy and Qatar were not accommodated.

The PageRank algorithm was used to rank the nodes of network based on their significance level (Khokhar, 2015). This algorithm was utilized to visually identify the most significant nodes by re-sizing and re-coloring them as illustrated in Fig. 5. The large size of a node and

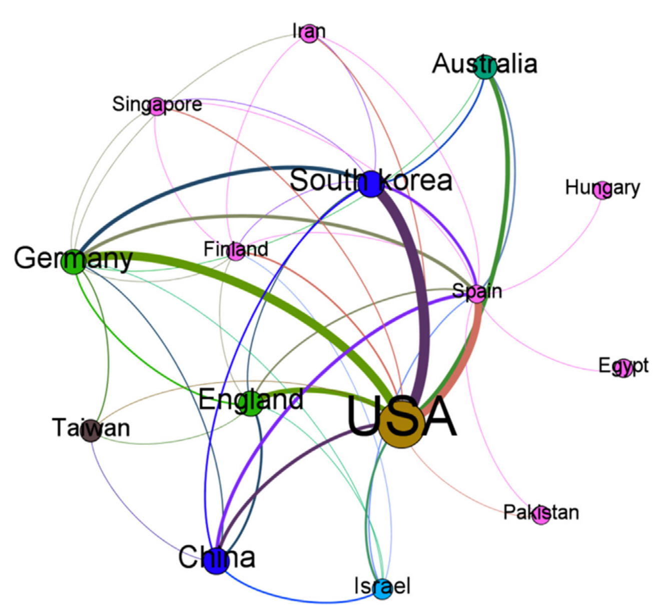


Fig. 5. Citation of countries.

font depicts the highly focused source for this knowledge area. Therefore, USA is found to be the most influential node indicating its role in the advancement of research in the body of literature (Martínez-Aires et al., 2018). It is due to the fact that this technology was originated in the USA and many companies have developed BIM software packages there. Strong links of USA with other countries like South Korea, Germany, Australia, England and Spain show a high level of collaborative research effort. While countries like Pakistan, Hungary and Egypt have deficient research in this body of literature. Therefore researchers present in these countries are encouraged to realign their research focus by addressing and studying technology based research problems which may directly help their AECO sectors.

3.4. Snowball sampling

Furthermore, in order to cover all of the related publications outside the selected journals, snowballing technique was applied by checking the pertinent citations of present dataset (Badampudi et al., 2015). Similarly, the applied technique in this research resulted in the addition of 27 articles.

The final dataset includes 97 relevant papers from different databases and their yearly distribution is shown in Fig. 6. It can be seen that the number of articles summarily become prominent in the year 2015 representing that the trend has been shifted towards BIM research. Among the journals, Automation in Construction has the largest number of articles while Safety Science has started publishing large number of content on the technological applications since recently.

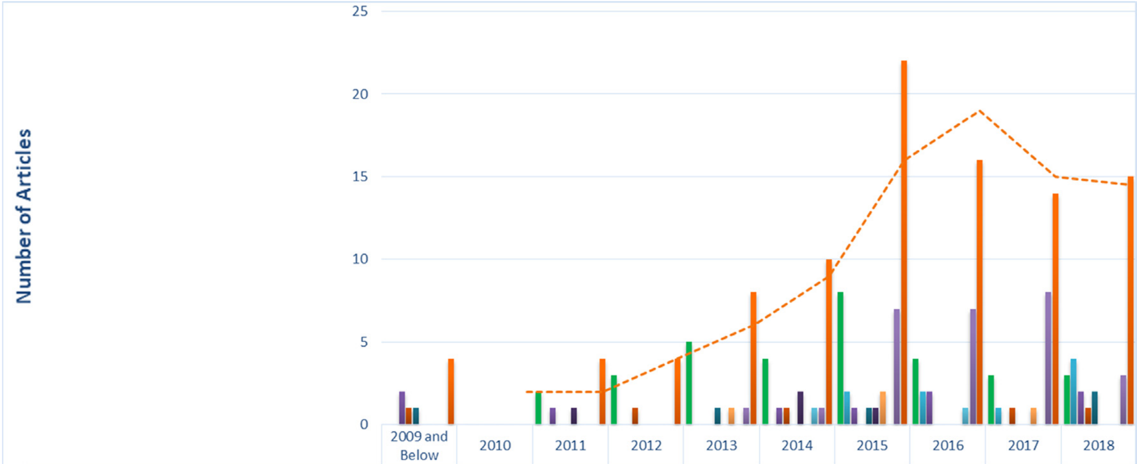
3.5. Content analysis

3.5.1. BIM application domains in safety management

One of the main objectives of this review is to identify the attributes of BIM and construction safety, which was only possible by a detailed scrutiny of all the selected articles. Therefore, final dataset was reviewed fully. The data was scrutinized for all the attributes of BIM and safety, and focus was not particularly on the relevance between them. The study revealed significant attributes in the relevant body of literature, which came out to be 21 for construction safety and 24 for BIM. A quantitative score was calculated for the identified safety attributes and their relative importance based on their frequency of occurrence which can be seen in Fig. 7.

Hazard recognition and hazard prevention are the most frequently used factors of safety in the application domain of BIM. Carter and Smith (2006) concluded that unidentified hazards pose the most problematic conditions and prevention techniques cannot be applied without proper hazard identification. Therefore, safety planning, which includes identification and prevention of hazards, is considered as a fundamental step towards safety improvement and is the frequent research area in body of literature (Azhar, 2017; Sulankivi et al., 2012). Further, worksite safety is also a recurring factor since most construction accidents occur directly on construction sites (H. Kim et al., 2016; Li et al., 2012). This motivates the researchers to focus on planning for jobsite safety (Akula et al., 2013). While factors like safety cost and language adoption are least significant in the literature of BIM and safety since adoption of BIM does not affect them. However, they are discretely significant as safety costs incur due to construction accidents (Ikpe et al., 2012; Yilmaz and Çelebi, 2015) and appropriate safety planning would lower down such costs. Further, language adoption adds into the effectiveness of communication which otherwise remains low due to immigrant workforce on construction sites. As BIM aids in overcoming language barrier (Nasir, 2017), many researchers have shifted their consideration towards safety training using BIM based visualization (Jaselskis et al., 2008; Trajkovski and Loosemore, 2006).

Similarly, job hazard analysis is a way to identify and analyze hazards in the planning stage by giving special attention to job tasks and related resources. It requires sufficient time and a plethora of



	2009 and Below	2010	2011	2012	2013	2014	2015	2016	2017	2018
Automation in Construction	0	0	2	3	5	4	8	4	3	3
Safety Science	0	0	0	0	0	0	2	2	1	4
Journal of Construction Engineering and Management	2	0	1	0	0	1	1	2	0	2
Journal of Information Technology in Construction	1	0	0	1	0	1	0	0	1	1
Journal of Computing in Civil Engineering	1	0	0	0	1	0	1	0	0	2
Advanced Engineering Informatics	0	0	1	0	0	2	1	0	0	0
Visualization in Engineering	0	0	0	0	1	0	2	0	1	0
Computer-Aided Civil and Infrastructure Engineering	0	0	0	0	0	1	0	1	0	0
Others (Snowballing)	0	0	0	0	1	1	7	7	8	3
Total	4	0	4	4	8	10	22	16	14	15

Fig. 6. Trend of published articles for construction safety and BIM.

information to comply with its structured mechanism. To aid this phenomenon, Zhang et al. (2015a) proposed construction safety knowledge ontology and explored its connection with BIM since it offers richness of design information. By simulating and visualizing safety information model, it was concluded that safety managers can efficiently plan and enhance their safety management practices by analyzing hazards. Furthermore, when the site information is integrated with BIM through sensors, safety personnel can monitor the unsafe performance of workers (Gu et al., 2014). In addition to monitoring workers performance, it is also necessary to observe severe worksite conditions that can cause serious injuries and illness. Therefore, Riaz et al. (2014) performed the integration of real-time sensors data with BIM to monitor the confined spaces present on construction sites which can safeguard the workers operating in such dangerous conditions.

3.5.2. BIM technology characteristics

Similarly, attributes of BIM were identified from the body of literature and only those attributes are displayed in Fig. 8 whose minimum frequency was 5. On top of the list is visualization which is portrayed as the most promising feature in the literature, since it can improve safety management by allowing the stakeholders to visually observe worksite conditions and get familiar with hazards beforehand (Azhar, 2017; Bouchlaghem et al., 2005; Hadikusumo and Rowlinson, 2004; Kim and Teizer, 2014). Further, automated rule based checking has got sufficient consideration in recent years and has been focused by many authors in their study (Luo and Gong, 2015; Malsane et al., 2015; Melzner et al., 2013; Zhang et al., 2015c). Hongling et al. (2016) performed the integration of design safety codes and OSHA regulations with BIM to automatically identify safety issues. They concluded that automated checking saves time and labor cost which is otherwise

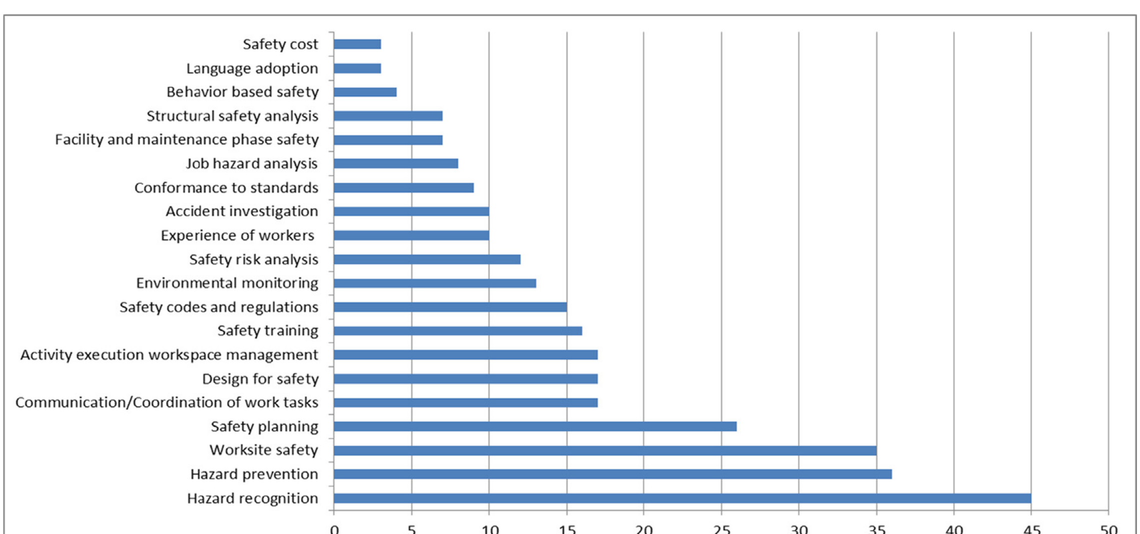


Fig. 7. Frequency of safety factors.

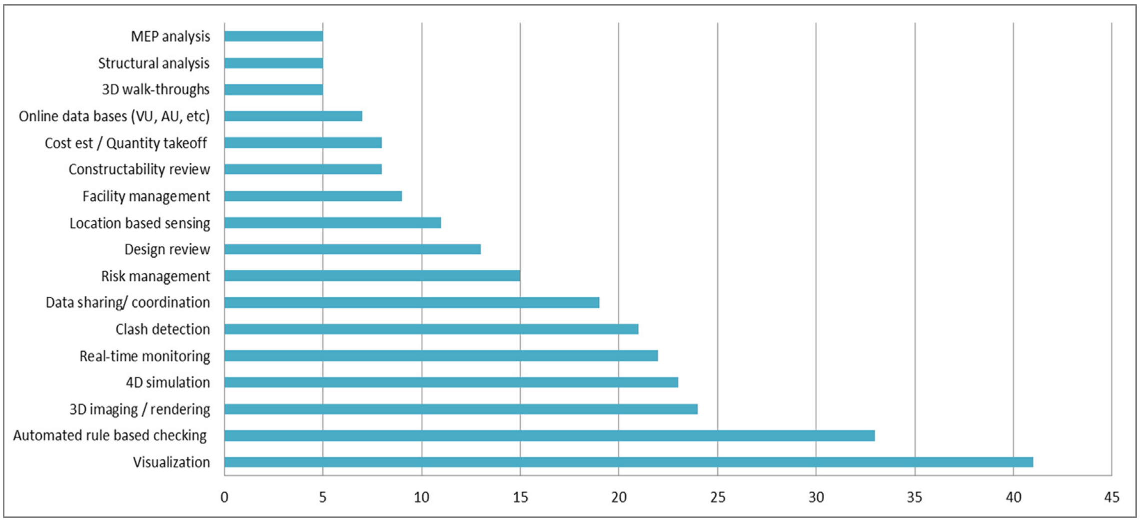


Fig. 8. Frequency of BIM attributes.

employed in improving safety management.

Finally, though MEP and structural analyses are undoubtedly the important features of BIM, they provide no significant role in this research area, justifying considerably low frequencies.

3.6. Project lifecycle analysis of articles

While distributing the identified articles into the project lifecycle phases, it was found that much of the work has been focused on design and planning phases of project while relatively less amount of work has been conducted for construction and operations phases as shown in Fig. 9.

Construction safety entails a special concern throughout the project lifecycle, from design phase to facility management of a project (Zhang et al., 2013). But the major contribution in worksite accidents are due to lack of efficient design and planning aspects (Gambatese et al., 2005). Waly and Thabet (2003) concluded that safety planning in the earlier phases of a project is a crucial step for best safety management practices. Most of the accidents occur during construction phase (Zou et al., 2007) and improper safety planning is the major contributing factor behind these high rates of fatalities (Azhar, 2017; Lappalainen et al., 2007). Therefore many researchers have focused on design and planning segment of projects (Ding et al., 2016; Kim and Teizer, 2014; Li et al., 2015; Malekitabar et al., 2016; Zhang et al., 2015c) which depicts the efficacy of BIM in preventing accidents through design (Qi et al., 2013; Rüppel and Schatz, 2011; Zhang et al., 2015b). Though Wetzel and Thabet (2015) highlighted the severe rate of injuries in the facility management phase of project while providing repair and maintenance services, relatively less amount of work has been done for providing safe practices in this phase. Most of the study practices involve identifying construction hazards with the help of visualization to control safety (Cheng and Teizer, 2010). The utilization of 4D models can be made both in the design and construction phases to detect workspace conflicts (Koo and Fischer, 2000). Zhou et al. (2012) showed

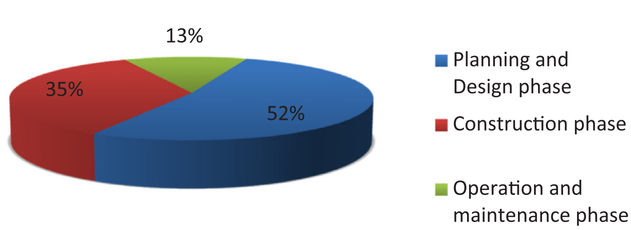


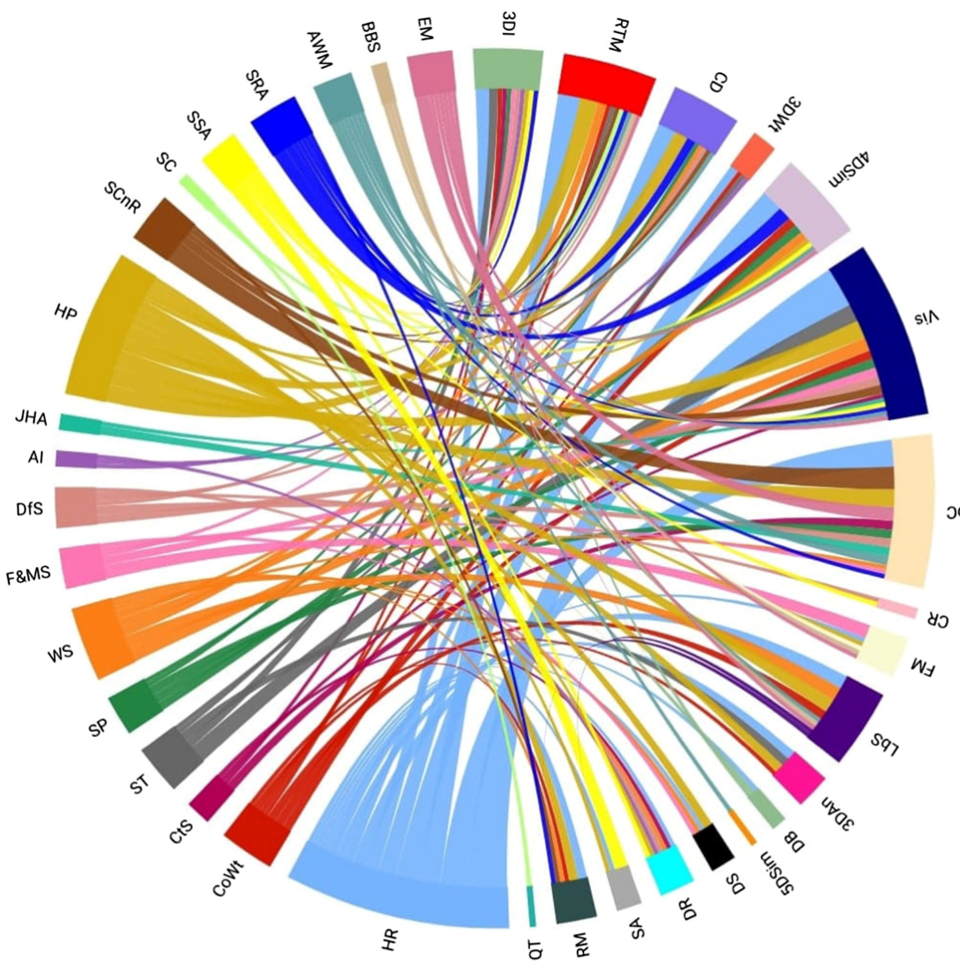
Fig. 9. Percentages of related publications in project lifecycle phases.

that a 4D model generated during design phase can be employed in safety planning for construction sites. Thus, Zhou et al. (2013) collected the information about construction components and their respective schedule in the design phase to generate 4D model, so that potential conflicts can be identified by automatic rule based checking, before construction starts. Some authors also focused on providing safety during emergency situations such as testing the building occupants response with fire emergency cases by developing a game using 3D BIM modeling (Rüppel and Schatz, 2011).

3.7. Relationship of BIM and safety domains in literature

A relationship matrix was developed for the identified attributes of BIM and construction safety, and their linkages were established based on their frequency of occurrence in the literature. The matrix is represented in the form of a Chord diagram which was coded using JavaScript, as shown in Fig. 10. The thickness of links shows the strength of correlation and width of an attribute shows its individual significance in comparison to others.

Of the identified factors, hazard recognition (HR) is the most influential factor of safety because of its maximum width and high number of links with features of BIM. In order to provide safe working environment and enhancing the chances of project success, it is important to identify hazards in the earlier phase of a project (Li et al., 2012). Hazard detection is essential because the construction tasks inherently involve risks and their knowledge is as important as the need for diminishing accidents (Mohammad and Hadikusumo, 2017). Hazard prevention (HP) also attained a significant position among safety factors and clearly depicts the high degree of correlation with features of BIM. Because once the hazards are identified, it is necessary to develop prevention strategies which can be done by ensuring safety codes and regulations (SCnR), and appropriate training of workers, reducing interruptions and compensations of the project (Ikpe et al., 2012; H. Kim et al., 2016). Similarly, visualization (Vis) is the most dominant feature of BIM with a much wider span and large number of correlation links. Visualization (Vis) is the elementary part of digital technologies; most of the workforce lacks technical expertise to better comprehend the outcome without picturing it (Nasir, 2017). Thus, visual representation helps in understanding the product and needed information (Chen et al., 2013; Rohrer, 2000). Therefore, visualization (Vis) has a noteworthy prominence amongst all aspects of BIM. Automated rule based checking (ArbC) also has a significant correlation linkages revealing a significant amount of work that has been conducted for safety management by the virtue of this feature. Zhang et al. (2013) developed a



Safety Factors --- HR: Hazard recognition; CoWt: Coordination of work tasks; Cts: Conformance to standards; ST: Safety training; SP: Safety planning; WS: Worksite safety; F&MS: Facility and maintenance phase safety; DfS; Design for safety; AI: Accident investigation; JHA: Job hazard analysis; HP: Hazard prevention; SCnR: Safety codes and regulations; SC: Safety cost; SSA: Structural safety analysis; SRA: Safety risk analysis; AWM: Activity workspace management; BBS: Behavior based safety; EM: Environmental monitoring
BIM Features --- 3DI: 3D imaging; RTM: Real-time monitoring; CD: Clash detection; 3DWt: 3D walk-throughs; 4DSim; 4D simulation; Vis: Visualization; ArbC: Automated rule-based checking; CR: Constructability review; FM: Facility management; LbS: Location-based sensing; 3DAn: 3D animation; DB: Online databases; 5DSim: 5D simulation; DS: Data sharing; DR: Design review; SA: Structural analysis; RM: Risk management; QT: Quantity take-off

Fig. 10. Chord diagram of relationship of BIM and safety.

framework for automated checking of safety rules and validated it with the help of a case study. Melzner et al. (2013) utilized the developed framework for identifying hazards in planning phase of a project and suggested protective measures and equipment required to eliminate safety hazards. Similar kind of effort was deployed by different researchers to enhance safety practices (Eastman et al., 2009; Sulankivi et al., 2012).

The strong relationship between hazard recognition (HR) and visualization (Vis) illustrates the usefulness of this approach for enhancing construction safety. Sadeghia et al. (2016) concluded that visualization (Vis) is the most valuable tool for positive safety practices. The traditional use of safety information on construction sites does not predict the factors involved in real jobsite environment, and makes it difficult to identify possible safety issues and communicate the right information to workers (Golparvar-Fard et al., 2009). The growing overseas workforce also requires a clear visual representation of safety hazards to sufficiently asses jobsite conditions (Azhar, 2017; Park and Kim, 2013). Hazard recognition (HR) has a strong correlation with automated rule based checking (ArbC) which helps to identify hazards without exploiting effort of safety experts in focusing visualization. Regional health and safety regulations are merged with 3D visualization tools and translated from human language into computerized parameters with the help of accident related components, thereby automatically highlighting the safety hazards (Hongling et al., 2016; H. Kim et al., 2016; Zhang et al., 2015a). Benjaoran and Bhokha (2010) developed a rule based system for height related risks because fall has high statistics in construction fatalities. The attributes such as element type, size, placement, activity and accident type were used for providing input. This helped in recognizing hazards and suggesting safety measures which can be approved by a safety professional.

Hazard recognition (HR) can also be done with the help of clash detection (CD) and 4D simulation (4DSim), and these features also show a significant association. Construction safety clashes are the inconsistencies among the crucial attributes of jobsite conditions, which can cause problems (Tixier et al., 2017). There are many activities on construction sites that run adjacent to one another. Thus, to minimize workspace conflict, a system was developed by Moon et al. (2014a) for automatic checking of workspace clashes using 4D simulations (4DSim) so that schedule of conflicting activities can be changed. Similarly, Marzouk and Abubakr (2016) developed a framework for selecting type and location of a tower crane at jobsites. The framework performed clash detection for crane operations using 4D simulation, which was used to identify and resolve the issue of parallel working cranes.

Location of resources on construction sites is usually manually monitored which requires experienced professionals but this approach is time consuming and error-prone (Cheng and Teizer, 2013; Zhang et al., 2015c). Real-time location system monitoring is considered an effective approach to identify and trace the location of resources such as personnel, materials and equipment (Li et al., 2016). One of the fundamental areas for application of real-time monitoring (RTM) is jobsite monitoring for safety augmentation (Cheng and Teizer, 2013). Therefore, hazard recognition (HR) has been performed by many researchers using real-time monitoring (RTM) and location-based sensing (LbS). Thus, hazard prevention (HP) can be implemented based on observations. Teizer (2015) demonstrated the reliability of localizing and monitoring the construction resources with the help of active visualization system. It was concluded that sensing and tracking of assets on construction sites help the professionals by saving time spent on safety monitoring, and can focus attentively on cost and schedule control. The inappropriate usage of personal protective equipment (PPE) causes many injuries and causalities, therefore a system was developed by Dong et al. (2018) for automatic identification and assessment of PPE by merging pressure sensors and localization technologies in BIM. The system has the ability to track workers location and dangerous situations, sending warning signals and assessing the location where PPE is necessary. It also provides feedback for hazard prevention (HP).

It is found that visualization (Vis) addresses the maximum number of safety aspects as compared to other features of BIM which exhibits its prominence as illustrated in Fig. 11 (see Fig. 10 for explanation of safety factors and BIM features). However, it has a relatively weak link with environmental monitoring (EM) and activity workspace management (AWM) which shows the amount of deficient research in these areas. Still, Riaz et al. (2014) illustrated that BIM has a strong potential for improved visualization for effective monitoring of workspace environment. There can be numerous hidden hazards on execution sites such as disturbed temperature and humidity levels mostly in confined spaces. Thus, utilizing the visualization feature of BIM and integrating it with wireless sensing technologies, environmental monitoring (EM) can be performed which would help in reducing possible fatalities (Arslan et al., 2014; Cheung et al., 2018; Sousa et al., 2014). Researchers must focus on activity workspace management (AWM) as it is one of the significant resources as well as constraints at a jobsite, and ineffective workspace management results in safety hazards and low quality (Choi et al., 2014; Zhang et al., 2007). As a conflict in schedule of activities creates difficulties for professionals to safely manage the workspace, therefore with the help of visualization (Vis) and simulation, algorithms were developed to actively manage activity workspace and minimize conflicts (Moon et al., 2014b).

Further, visualization (Vis) has proven to be substantial in safety training (ST) as it helps in overcoming language barrier which workers face during training session. Most of the immigrant workforce faces difficulty in understanding the training material. Therefore, BLR (2007) suggested using visual representation for providing training to workers. A survey conducted by Demirkesen and Arditi (2015) demonstrated that majority of the US companies consider effective safety training as a fundamental step for improving safety management. Training for safety was conducted on a group of construction management students to test the effectiveness of visualization approach, and applicability for industry practices. The students were asked to share observations after the training session which was conducted in two ways; first test was

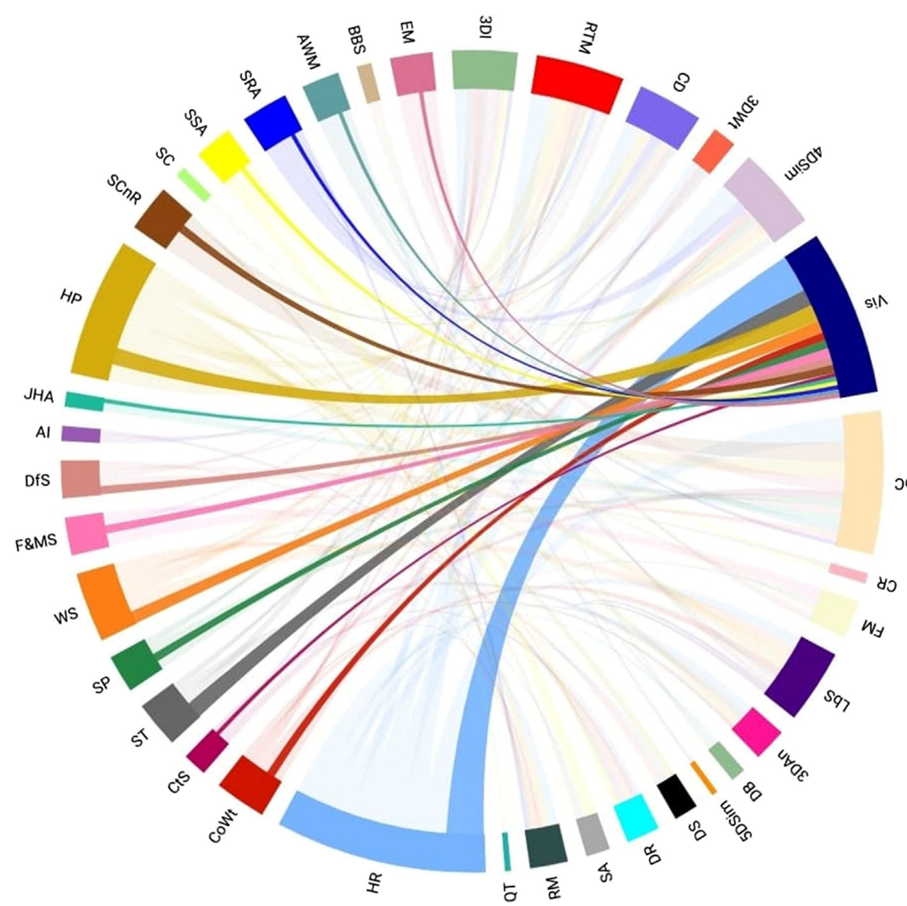


Fig. 11. Correlation of visualization.

following traditional training techniques, while the second utilized visual-aids. The results came out to be positive and appreciable for visualization (Clevenger et al., 2015).

Safety planning (SP), the first and foremost aspect for providing any safety practice, includes hazard recognition (HR) and hazard prevention (HP) as the main components of safety management. While performing safety planning, all the hazards as well as near misses must be observed and reported to construction site personnel so that mitigation strategies can be developed (Cambraia et al., 2010; Marks et al., 2014). Near miss reporting information, like hazard recognition (HR) and worksite safety (WS) planning, can be greatly improved by visualization (Vis) (Elbeltagi et al., 2004; Hallowell et al., 2013). Thus, Shen and Marks (2015) developed a database for near miss information in BIM, so that reporting and visualization can be performed. This should be considered while planning for safety, so that safety professionals can visualize near misses throughout the construction phase. Similarly, Zhang et al. (2015b) developed automatic checking of safety hazards and the understandable visualization of those identified along with a protective system for their mitigation.

The large number of casualties and injuries results in an excessive cost and work time loss which ultimately affect the safety cost (SC) of project (Huang et al., 2011). BIM might not directly address the aspect of safety cost but it helps in lowering down the cost spent on accidents due to its effectiveness in improving construction safety (Zuppa et al., 2009). However, the body of literature lacks such a framework for enhancing safety through BIM features. To bring down the statistical figures, experts have been focusing towards identifying the root cause of many injuries, out of which unsafe human behavior came out to be the most significant with a large number of injuries from lifting or carrying, trapped between objects and slip, trip or fall (Labor Department Hong Kong, 2016). To mitigate unsafe behavior from human nature, Chen and Tian (2012) suggested behavior based safety (BBS)as the most effective approach. However, less amount of work has been conducted in different dimensions of this knowledge area, such as analyzing the impact of safety culture on workers behavior and relationship between workers and safety superintendents (Zhang et al., 2017). As depicted in Figs. 9 and 10, the influence level of this knowledge area is relatively small and needs due consideration.

4. Conclusion and practical applications

It is concluded from the detailed inspection of literature that there is comparatively lesser research in the area of BIM and safety management. Training is an essential step towards enhancement of construction safety but there is no substantial literature on delivery of safety knowledge to workers on site using digital technologies. Therefore, efforts are required for providing safety training by the virtue of visualization feature of BIM that can help in understanding the safety codes and regulations in a graphical and comprehensible form. Han et al. (2009) and Clevenger et al. (2015) also focused on the need of research for safety training by using visualization technologies. Further, behavioral safety must be studied and addressed using the features of BIM because the reluctant human nature causes many injuries and fatalities. Since their constant presence on site, this issue can be resolved using the BIM features. The developed relationships of BIM features and safety factors can help researchers identify the best feature for a particular safety aspect.

This study highlights the importance of investment for safety improvement. Safety cost is the amount required to improve safety practices and it can be spent in the form of training, PPE expenditures, technological applications and others (Feng et al., 2014). Therefore, the focus of studies should be placed towards safety investment and its influence can be calculated by cost-benefit analysis, rate of return and payback period calculations. The first and foremost step towards adopting any new technology is knowing its financial impacts. Thus, future research can be performed for safety cost calculation of projects incorporating BIM for safety improvement. Cost required for training, PPEs and personnel wages should be considered, and technology investment payback period calculations are required for industry professionals to encourage the adoption of BIM, especially in the developing part of the world. This will motivate the industry professionals in adopting BIM for safety improvement, which would ultimately help in lowering down the fatality and injury rates on construction sites. Similarly, identifying the root cause of accidents will reduce the fatality rate and help in designing for safety.

Current studies focus on type of accident and how they occur but the body of literature lacks in information about why these accidents occur. Effective investigation addresses every aspect of an accident and BIM can be used for this purpose to reconstruct the events and sequence of their occurrence (Azhar and Behringer, 2013). Therefore, future research should focus on providing accident investigation strategies using BIM. A database can be developed for previous accidents highlighting every aspect of incident, helping the professionals in hazard prevention later on. This would help safety professionals assess the previous accidents and the aspect that require sufficient consideration during construction.

Similarly, keeping in view the emerging need of BIM for safety management, a dedicated BIM plugin is required for improving construction safety. Such a plugin will position BIM centrally and turn it into a decision support tool for safety related matters. The proposed plugin should address the major aspects related to internal project information as well as the site related detail. Most of the fatalities occur on construction site, therefore sensing technology like drone can be utilized on site for providing real-time input to BIM. The database in BIM must include all the safety standards present in regulations and literature. This effort would help in automating the identification and prevention of construction site hazards related to logistics as well. Several such works are reported in literature which automate the management tasks; such as Chen and Nguyen (2017), who developed a Revit LEED plugin for integrating web map service with BIM; Ahmad and Thaheem (2017) who designed a specialized plugin to integrate social and economic sustainability concepts of building projects into BIM (Ahmad and Thaheem, 2018) and Ahmad et al. (2018), who developed a conceptual model of a BIM plugin for risk management.

The study also reveals many features of BIM, each of which holds a significant importance and can be used for construction safety. But the application of 3D walk-through is worthwhile as it can be used for hazard identification, safety training and communicating safety plans to workers (Azhar, 2017; Azhar and Behringer, 2013). However the amount of work using this feature is significantly low, therefore focus should be shifted towards safety improvement using 3D walk-throughs. This emerging BIM feature will greatly add into real-time understanding of safety issues. Furthermore, poor communication with workers is the major factor behind many fatalities, thus future research can utilize this prominent BIM feature for overcoming communication issues and identification of hazards. It would help in lowering the cost and time required for safety trainings and daily meetings, and safety will consequently improve.

This research is limited by its selection criterion of a minimum of 2 papers for inclusion of a journal whose papers can be reviewed to draw upon the overall body of knowledge. Another limitation of this research is the usage of .txt files for VOSviewer which limited the bibliometric analysis to documents sourced through WoS only. Despite no effect on the quality of bibliometric analysis due to this selection, it is still recommended that future reviews can extend the limitations of inclusion criteria and use other file types to include a larger dataset for bibliometric analysis.

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