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A Science Mapping Approach Based Review of Construction Safety Research

- The study applied science mapping approach in reviewing construction safety research.
- Mainstream keywords such as BIM were identified in existing literature.
- Influential journals, scholars, and articles in construction safety were evaluated.
- An in-depth qualitative discussion identified existing research topics and limitations.
- A research framework was proposed by linking mainstream topics into future research directions.

Abstract

This study adopted a three-step holistic review approach consisting of bibliometric review, scientometric analysis, and in-depth discussion to gain a deeper understanding of the research development in construction safety. Focusing on a total of 513 journal articles published in *Scopus*, the influential journals, keywords, scholars, and articles in the domain of construction safety were analyzed. For example, simulation and fall from height related topics, although not with the highest occurrence of being studied, had the highest impact in terms of average citation received per year. It was found that research in the recent 10 years have been extended to the developing countries and regions with a more variety of research topics, such as BIM, and data mining, etc. Articles related to applying BIM in safety management received the highest average normalized citation. A follow-up qualitative discussion targeted three main objectives: summarizing mainstream research topics, identifying existing research gaps, and proposing future research directions. Five main categories were aligned, namely safety climate and safety culture, application of information technologies, worker-oriented safety, safety management program, and hazard recognition and risk assessment. Based on the above, a framework and future research directions were proposed which could serve both the academic community and practical fields in multiple themes within construction safety, including: an adaptable safety climate and safety culture model; prototypes, continuous development, and readiness of applying information technologies in safety management; subgroups factors linked to cognitive models of workers' safety perceptions and behaviors; and artificial intelligence and smart technologies into safety program management.

Keywords: construction safety; human factor; scientometric review; science mapping; literature review

1. Introduction

Construction is regarded as one of the most unsafe industries worldwide (Lingard and Rowlinson, 2015). For example, the incident rates, which represent the number of injuries and illnesses in the construction industry, were significantly higher than the national average among all industries in the U.S. (U.S. Bureau of Labor Statistics, 2016). Similar challenges exist in other countries (Fang et al., 2016). Research in improving the safety performance of the construction industry has been continuing in the past decades, covering multiple areas such as safety performance measurement (Liu et al., 2018), safety program (Chen and Jin, 2013), and human factors (Liao et al., 2018). In recent years, due to the growing application of digital technology such as BIM (i.e., Building Information Modeling) in construction, researchers have started applying BIM in enhancing safety planning and site monitoring (Cheung et al., 2018; Choe et al., 2014). Adopting the literature review is an expedient approach to gain an in-depth understanding of a research domain (He et al., 2017). So far there has been limited studies adopting a holistic review of human factor-oriented construction safety literature that covers these aforementioned issues (e.g., safety program, BIM, and human factors, etc.)

Several existing review-based studies in construction safety such as Swuste et al. (2012), Martínez-Aires et al. (2018), and Mohammadi et al. (2018) are based on the manual reviews, which could be prone to subjectivity or even biasedness as indicated by Hosseini et al. (2018). Although scientometric analysis approach (Song et al., 2016; Zhao, 2017) has been adopted in the field of construction engineering and management to address the subjectivity issue, these existing scientometric review-based studies were limited to self-exploratory topics such as the most productive scholar, the most influential journal, and most frequently searched keywords (Jin et al., 2018). The level of details presented in these previous reviews could be enhanced (Jin et al., 2018). This review-based study applied the science mapping approach by reviewing journal articles published in the domain of construction safety. The objectives of this study include: 1) applying science mapping approach to analyze the influential journals, keywords, scholars, and articles in the domain of construction safety; 2) analyzing the existing mainstream research topics in construction safety; 3) discussing the limitations or gaps of existing research in the construction safety domain; and 4) proposing the research framework guiding future scholarly and research work. This review-based study introduces the science mapping approach into the domain of construction safety, and provides recommendations for future-research in sub-themes within construction safety.

2. Methodology

This study adopted a three-step literature review approach summarizing the research domain of construction safety. The science mapping approach which consisted of bibliometric analysis and scientometric analysis, was adopted in the review. The detailed workflow of the review is illustrated in Figure 1.

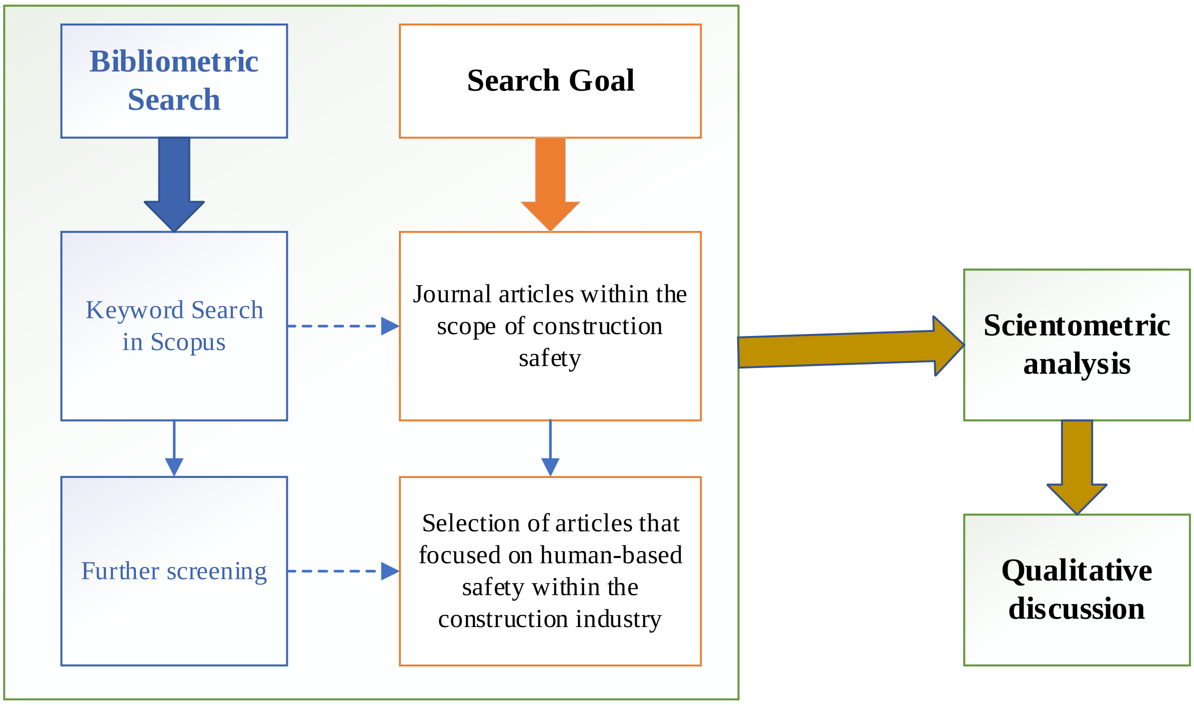


Fig. 1: Description of the three-step literature review process

2.1.Bibliometric search

The first step of the review was the bibliometric search in *Scopus*. The keyword "construction safety" was input to search literature published in *Scopus*. Scopus covered more journals and more recent publications compared to any other available digital sources (e.g., *Web of Science*) (Aghaei Chadegani et al., 2013). Initially, *1,738* documents were found. These documents were further screened by including only journal articles published in English. Conference papers were excluded from the sample because they have been released in a large quantity but with less valuable or useful information compared to journal articles (Butler and Visser, 2006). After this initial screening, totally *633* articles remained in the literature sample. According to Fig.1, further refinements of the remaining *633* articles were studied of their titles, abstract, and keywords in details. Some articles, such as Zhang et al. (2018b), although with the term "construction safety" in its abstract, did not focus on safety in construction. Similar articles that did not focus on safety issues in the construction industry were removed. Another type of articles (e.g., Song et al., 2018), although within the context of construction industry, focused on risk assessment which was wider than the scope of safety risks. Similar articles were also excluded. Further, it should be noticed that the the scope of this review-based study is human-centered safety management, it covered the safety planning and site management, but excluded other safety issues that do not direct focus on construction employees' safety, for example, structural or material safety for buildings (Peng, 2017). After the final round of screening, ultimately a total of *513* journal articles were selected as the literature sample for the follow-up scientometric analysis.

2.2. Scientometric analysis

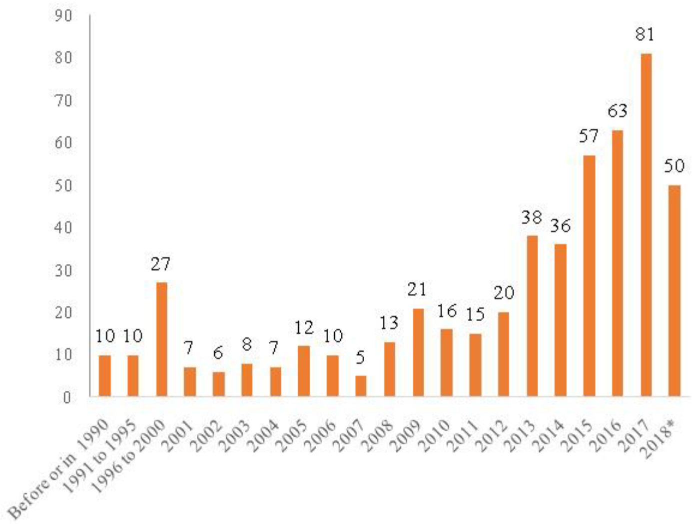
The second step of the review involved a scientometric analysis method by utilizing the text-mining tool *VOSViewer* (van Eck and Waltman, 2010). More background information of scientometric analysis can be found in Hosseini et al. (2018). *VOSViewer* creates distance-based visualizations of networks where the distances among nodes show the level of closeness among them (Van Eck and Waltman, 2014). It is suitable for visualizing larger networks with special text mining features (Van Eck and Waltman, 2014). Using *VOSViewer*, literature sample obtained from the bibliometric search was transported into *VOSViewer* for scientometric analysis, which further generated results related to the influences of journals, keywords, scholars, and articles in the domain of construction safety.

2.3.Qualitative discussion

Based on the keyword analysis as well as articles analyzed in the prior step, the follow-up qualitative discussion aims to provide an in-depth evaluation of the three main research objectives related to the mainstream research topics in the domain of construction safety, the current research gaps or limitations, as well as the future recommended research work. Finally a framework linking the existing research topics to future directions is proposed for scholars within the academic community of construction safety to continue the research work of construction safety.

3. Results

The *513* journal articles were firstly summarized according to their publication year. Figure 2 display the articles’ distribution of publication years.



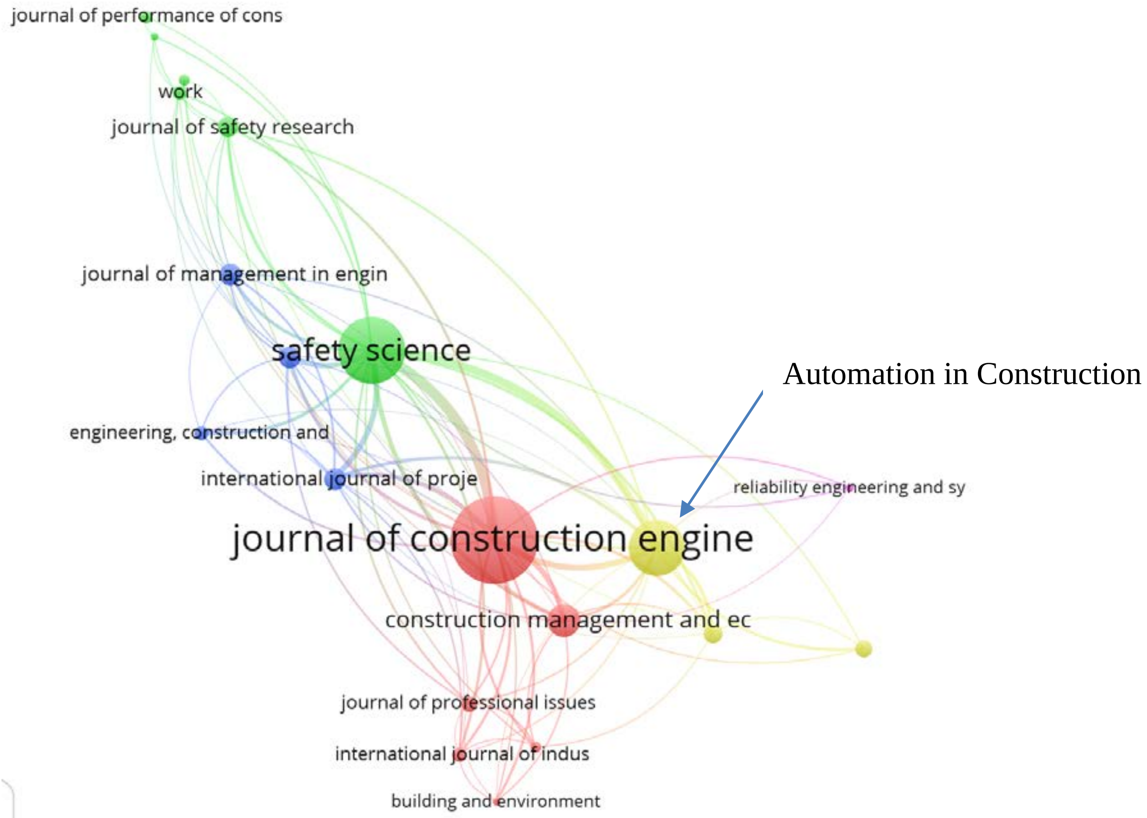
*: articles published in 2018 was up to the mid-April, hence the annual article in 2018 is incomplete.

Fig. 2. Distribution of journal articles by publication time

Fewer articles were published before 2000, especially before 1990. Therefore, these earlier articles were combined based on a five-year range from before 1990 to 2000. Articles published starting in 2001 are counted on the annual basis. It is seen from Fig. 2 that more articles have been published since 2012. Afterwards, the number of articles has been undergoing significant increase on a yearly basis. It is expected that more research work will be published in construction safety, which is an everlasting research domain in the field of construction engineering and management.

3.1.Journal sources

Besides the annual number of articles published, the journal sources of them were also summarized. Setting the minimum number of articles and minimum citations at *3* and *20* respectively in *VOSViewer*, *20* out of totally *136* journals met the thresholds. According to the node and font sizes, it is seen in Fig. 3 that *Journal of Construction Engineering and Management (JCEM)* has been the most productive journal in terms of total number of publications, followed by *Safety Science*, and *Automation in Construction*. The colors and connections lines indicate the inter-relatedness among journals, showing journals that have cited each other's articles. For example, these journals have been actively citing each other: *JCEM*, *Safety Science*, *International Journal of Project Management*, and *Construction Management and Economics*.



Note: 1. journal names may not be fully spelled out in *VOSViewer;* 2. Automation in Construction is denoted in Fig. 3 outside the originally generated mapping in order to avoid the over-crowdedness of fonts.

Fig. 3. Visualization of journal sources that publish construction safety research

A more quantitative measurement of the influence of journals is provided in Table 1.

Table 1. Quantitative summary of journal impacts in construction safety research

Journal	**Number of publications**	**Total Citation**	**Norm. Citation**	**Avg. Pub. Yr.**[1]	**Avg. Citation**	**Avg. Norm. Citation**[2]
Automation in Construction	46	928	101.52	2015	20.17	2.21
Reliability Engineering and System Safety	3	88	6.09	2013	29.33	2.03

International Journal of Project Management	12	518	20.83	2011	43.17	1.74
Safety Science	60	1964	102.21	2014	32.73	1.70
Building and Environment	3	177	4.93	2004	59.00	1.64
Journal of Computing in Civil Engineering	8	109	11.15	2015	13.63	1.39
Accident Analysis and Prevention	12	181	15.83	2013	15.08	1.32
Journal of Architectural Engineering	4	122	5.10	2002	30.50	1.27
Journal of Construction Engineering and Management	90	1855	103.87	2011	20.61	1.15
Journal of Management in Engineering	12	134	13.19	2013	11.17	1.10
Construction Management and Economics	21	391	21.40	2008	18.62	1.02
International Journal of Industrial Ergonomics	6	191	5.83	2009	31.83	0.97
Journal of Professional Issues in Engineering Education and Practice	7	111	6.61	2013	15.86	0.94
Applied Ergonomics	3	25	1.94	2015	8.33	0.65
Journal of Safety Research	11	199	6.92	2011	18.09	0.63
Engineering, Construction and Architectural Management	6	88	3.48	2013	14.67	0.58
Journal of Performance of Constructed Facilities	5	37	2.88	1998	7.40	0.58
Journal of Civil Engineering and Management	9	46	4.65	2016	5.11	0.52
American Journal of Industrial Medicine	4	76	1.78	2005	19.00	0.44
Work	6	50	2.37	2007	8.33	0.39

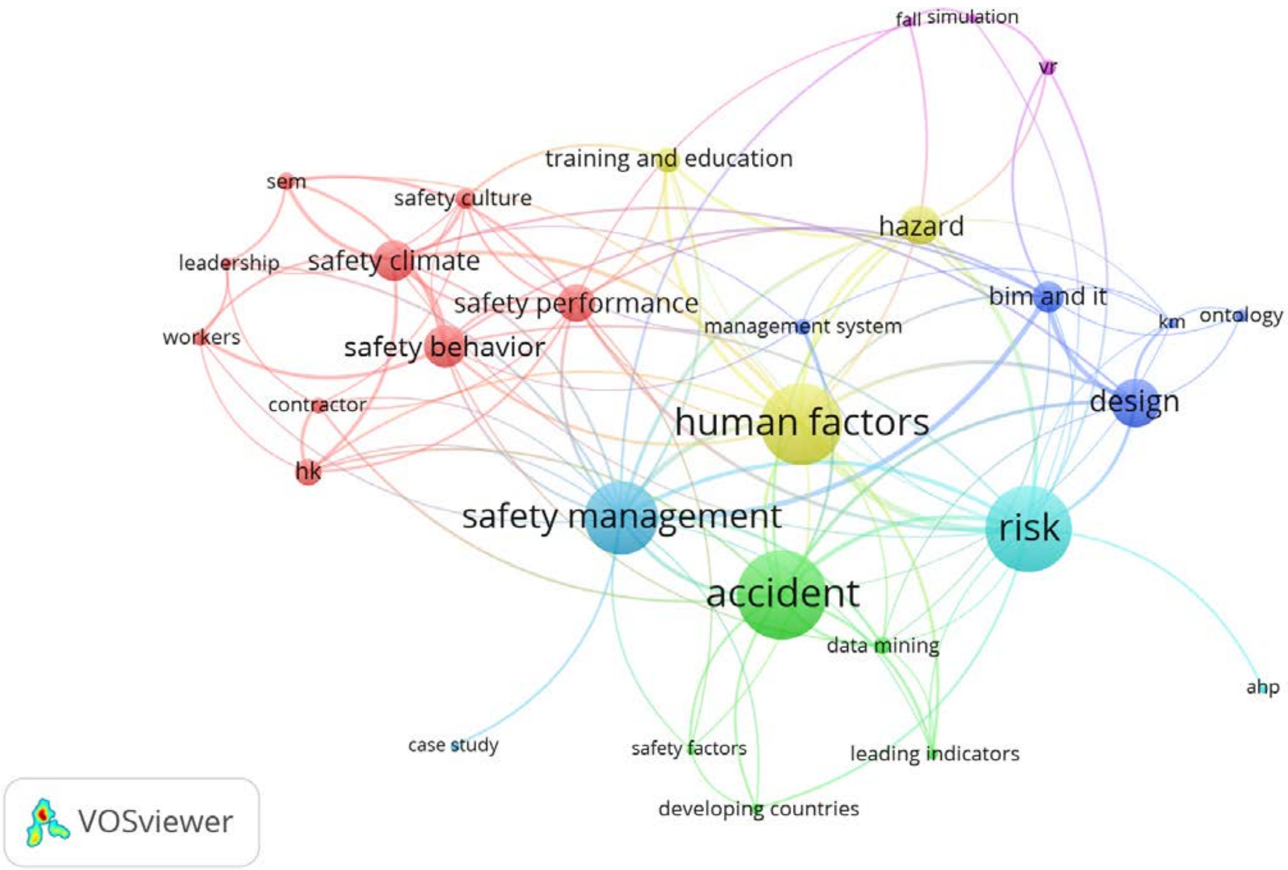
[1]: Ave. Pub. Yr denotes the average publication year of articles published in the given journal.

[2]: The Ave. Norm. Citation represents the normalized number of citations of a journal, document, author, or an organization. It equals the total number of citations divided by the average number of citations published in the same year. The normalization corrects the misinterpretation that older documents have more time to receive citations than more recent one(van Eck and Waltman, 2017). The Norm. Citation in Table 1 measures the citation of all the articles within the same journal, while the Ave. Norm. Citation represents the normalized citation per article, it is calculated by dividing the Nor. Citation by the number of articles.

Journals in Table 1 are listed according to their Ave. Norm. Citation. It is found that these two journals(i.e., *Automation in Construction*, and *Reliability Engineering and System Safety*) are most influential in construction safety research in terms of the Ave. Norm. Citation. In terms of number of articles and total citations, *Safety Science* and *JCEM* are the two most productive journals publishing research in construction safety. The Avg. Pub. Yr., which measures the average year of publication of all articles published in the same journal, is a measurement of the recentness of published research from the given journal. It can be seen that the recentness of published articles vary somewhat significantly. Journals including *Automation in Construction*, *Applied Ergonomics, Safety Science*, and *Journal of Civil Engineering and Management* published articles in the construction safety domain actively. In contrast, other journals seem not continuing active in published articles in construction safety, such as *Building and Environment*, *Construction Management and Economics*, and *Journal of Performance of Constructed Facilities.*

3.2.Keyword analysis

Keywords represent core contents of existing studies and describe research topics within a given domain (Su and Lee, 2010). Co-occurrence of keywords demonstrate the inter-closeness among them. By using “Author Keywords” and “Fractional Counting” in *VOSViewer* recommended by van Eck and Waltman (2014), and by setting the minimum occurrence of keywords at *4* in *VOSViewer*, *64* out of the totally *1,260* keywords were initially selected. Further work was performed to remove general keywords, such as “construction safety”, “safety”, “construction industry”, and “construction site”, etc. Some other keywords with the same semantic meaning, such as “BIM” and “Building Information Modeling”, were combined. The second-round text mining of research keywords was performed to eliminate general keywords and to combine semantically consistent keywords. Finally, *29* keywords were generated from the science mapping shown in Fig. 4. These keywords have been more frequently used in previous research of construction safety, including “accident”, “human factor”, “risk”, and “safety management”. The connection lines in Fig. 4 show the inter-relatedness between a pair of keywords. For example, human factors closely related to employee’ safety behavior, which covers studies focusing on correcting workers’ unsafe behavior through proper safety management (Guo et al., 2017b). The keyword “design” highlights design for safety in construction, and it is found with close links to BIM and IT, ontology, and knowledge management (KM). The keyword "hazard" covers hazard identification, hazard control, and hazard assessment. Fall is found with close connection with hazard, as it is one of the most common safety hazards on-site (Al-Kaabi and Hadipriono, 2003).



Note: 1. 2. VOSViewer could only display small-cased letters. For example, "bim and it" means BIM and IT, or Building Information Modeling and Information Technology; 2. SEM in Figure.2 stands for structural equation modeling; HK is Hong Kong; AHP means analytic hierarchy process.

Fig. 4. Visualization of author keywords from the literature sample

Keywords in Fig.4 are divided into several clusters. Keywords within the same cluster generally have closer internal relationships. For example, safety climate is often co-studied with safety culture in the same article. The distances and connection lines between keywords in Fig.4 indicate the inter-relatedness among them. For example, BIM and information technologies are found with close relationship with design for safety, knowledge management, and ontology; *safety behavior*, *human factors*, and *safety management* are closely related to each other. The font size indicates the frequency of the keyword that has been studied in the selected literature sample. These most frequently studied keywords include *safety management, accident, human factors, risk, and design*. They are further summarized in Table 2, based on the occurrence of them in the literature sample, average year of publication (i.e., Avg. Pub. Yr.), Average citation number (i.e., Avg. Citation), and average normalized citation (i.e., Avg. Norm. Citation).

Table 2. Quantitative summary of journal impacts in construction safety research

Keyword	**Occurrence**	**Avg. Pub. Yr.**	**Avg. Citation**	**Avg. Norm. Citation**
Simulation	4	2013	63.3	3.22
Fall	4	2015	51.5	2.57
Leading Indicator	5	2015	28.6	2.13
Knowledge Management	4	2015	23.3	1.79
SEM	8	2016	6	1.78
BIM and IT	16	2016	16.3	1.68
Case Study	4	2016	19	1.66
Contractor	7	2009	24.4	1.63
Safety Behavior	22	2016	18	1.48
Training and Education	12	2014	23.6	1.42
Ontology	6	2015	13	1.29
Design	26	2014	26.3	1.27
Safety Management	41	2014	13.7	1.23
Risk	49	2014	19.5	1.21
Management System	7	2011	59	1.2
VR	7	2015	21.4	1.18
Hazard	20	2015	11.6	1.17
Safety Climate	21	2014	31.6	1.15
Human Factor	46	2015	12.2	1.1
Safety Culture	10	2014	28.7	1.03
Developing Country	5	2010	7.4	1
Safety Performance	19	2014	10.8	0.94
Accident	51	2010	17.4	0.84
HK	13	2011	28.2	0.81
Data Mining	8	2015	6.6	0.8
Leadership	5	2015	7	0.73
Safety Factor	4	2013	16	0.54
Worker	7	2017	0.4	0.27
AHP	4	2016	0.5	0.1

It is noticed that keywords listed in Table 2 follow the ranking of Avg. Norm. Citation. It is indicated from Table 2 that keywords with the highest occurrence do not necessarily have the highest Ave. Citation or Avg. Norm. Citation. For example, keywords with highest Avg. Norm. Citation include *simulation*, *fall*, and *leading indicators*. It is indicated that studies focusing on applying simulation in safety planning (Goh and Askar Ali, 2016), accidents or risks caused by fall hazard (Cheung and Chan, 2012), or developing indicator system for evaluating safety performance or safety levels (Guo et al., 2017a) are likely to have higher impact in the research community of construction safety. The Avg. Pub. Yr. shows the recentness of keywords being studied and published. It is seen that most keywords listed in Table 2 are being studied in recent years except *contractor*, *developing countries*, and *accident*, which happen to be more traditionally studied keywords. These more emerging keywords include *workers*, *SEM* (i.e., structural equation modeling), *AHP* (i.e., analytical hierarchy process), *BIM and IT, safety behavior, and case study*. Observations of Fig.4 and Table 2 could lead to the following clusters of keywords that represent the mainstream directions of research in construction safety:

1. Safety climate and safety culture, which represent proactive indicators of safety performance, are highly linked to safety behaviors of workers. Leadership from contractors and other stakeholders (e.g., owner) all have significant impacts on safety culture (Wu et al., 2016). These safety site issues have been emphasized from research conducted in Hong Kong such as Wong et al. (2009) and Ju and Rowlinson (2014). SEM (Sunindijo and Zou, 2012) has been one of the main researhc methods in the studies of safety climate and safety culture.
2. Information technology (e.g., BIM) has been playing a more significant role in safety management. BIM has been displaying its influence in safety design and knowledge management (Tixier et al., 2016; Zhang et al., 2015a). Ontology is closely related to

information technologies in developing knowledge-based safety system (Guo and Goh, 2017; Lu et al., 2015).

3. Besides BIM, using other latest digital technologies such as VR (i.e., virtual reality), AR (i.e., augmented reality), and game engine in safety management, including training (Sacks et al., 2013) by creating accident scenarios (Park and Kim, 2013). These acvitity games in VR or AR create the simulation representing site danger scenarios for safety training and education (Le et al., 2015).
4. Data analytics such as data mining are being applied in construction safety research, specifically inhazard assessment (Hsueh et al., 2013), accident prediction (Rivas et al., 2011), and managing safety database from accidents (Goh and Ubeynarayana, 2017). Therefore,data mining is widely applied in adopting leading indicator (e.g., safety compliance) for safety performance prediction (Salas and Hallowell, 2016).
5. Analytical hierarchy process(AHP) is being widely applied in safety risk management, including risk analysis (Ardeshir et al., 2016) and safety level assessment (Huang et al., 2018).
6. Safety management programs covering training and education form a key part in the management system. Various studies (Chen and Jin, 2012; Li et al., 2018b) can be found introducing effective site safety programs addressing human factors and hazard assessment.Human factors in safety is an issue that has been idenfied to cause management failure (Kim et al., 2014).
7. Case study is another main research methodology is evaluate and test the effectiveness of newly developed management system or process, such as risk assessment model (Ning et al., 2018), worker safety behavior monitoring system (Li et al., 2015a), and decision-making in safety planning (Priemus and Ale, 2010).

3.3.Comparison of keywords between subsamples of literature

Continued from the keyword analysis, the literature can be further divided into two subsamples according to their years of publication. A total of *115* articles were published before 2009, with the first one appearing in *Scopus* in 1982. The remaining *398* articles were published during or after 2009. The separate mapping of keywords are demonstrated in Fig. 5 and Fig. 6, which allow the comparison of mainstream research keywords between the two subsamples (i.e., from the recent decade and before 2009). Compared to the keywords in the recent ten years, fewer keywords are found in Fig. 5. Literature before 2009 focused more on accidents, which were used as the main safety performance measurement (Ai Lin Teo and Yean Yng Ling, 2006). The causes of higher accident rates were evaluated, stressing the importance of safety training (Enshassi et al., 2007) and safety climate (Strahan et al., 2008). Compared to these earlier research topics in construction safety, more recent keywords emerging in the recent decade include “BIM and IT”, “VR” (i.e., Virtual Reality), “SEM” (i.e., structural equation modeling), “data mining”, and “AHP” (i.e., analytic hierarchy process). It is indicated that BIM and more advanced decision making tools (e.g., AHP) have been gaining wider applications in construction safety management in recent years. BIM, as the recently emerging digital technology, is gaining more application and research in assisting design for safety. Other digital technologies, such as VR, are also gaining its popularity in safety training, as discussed by Li et al. (2018a).

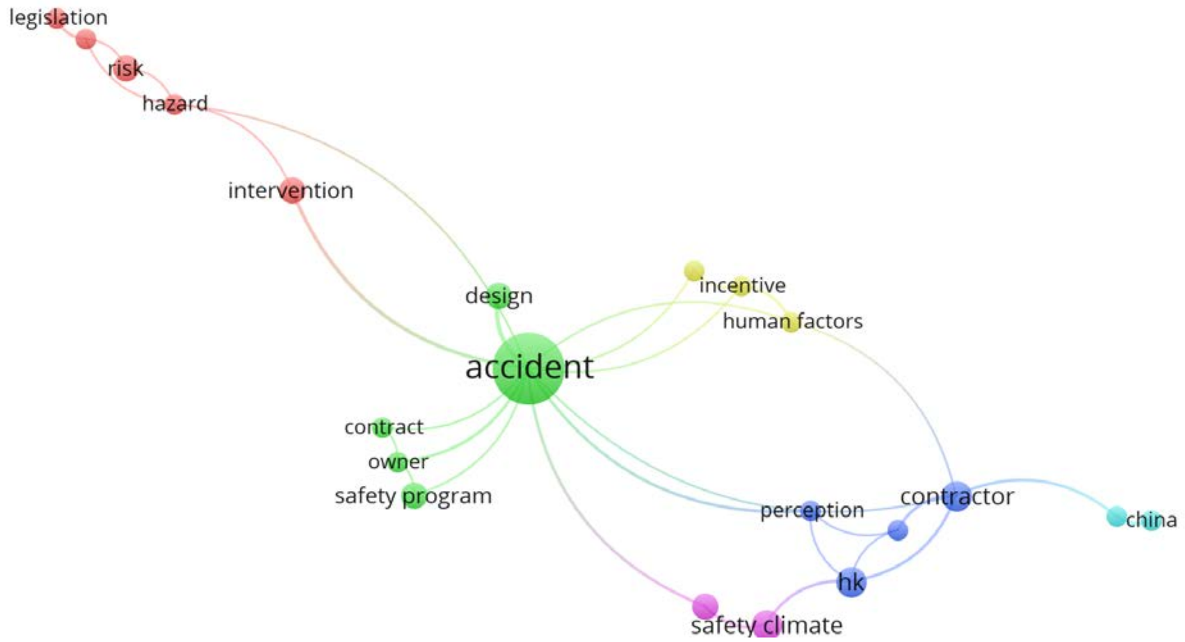
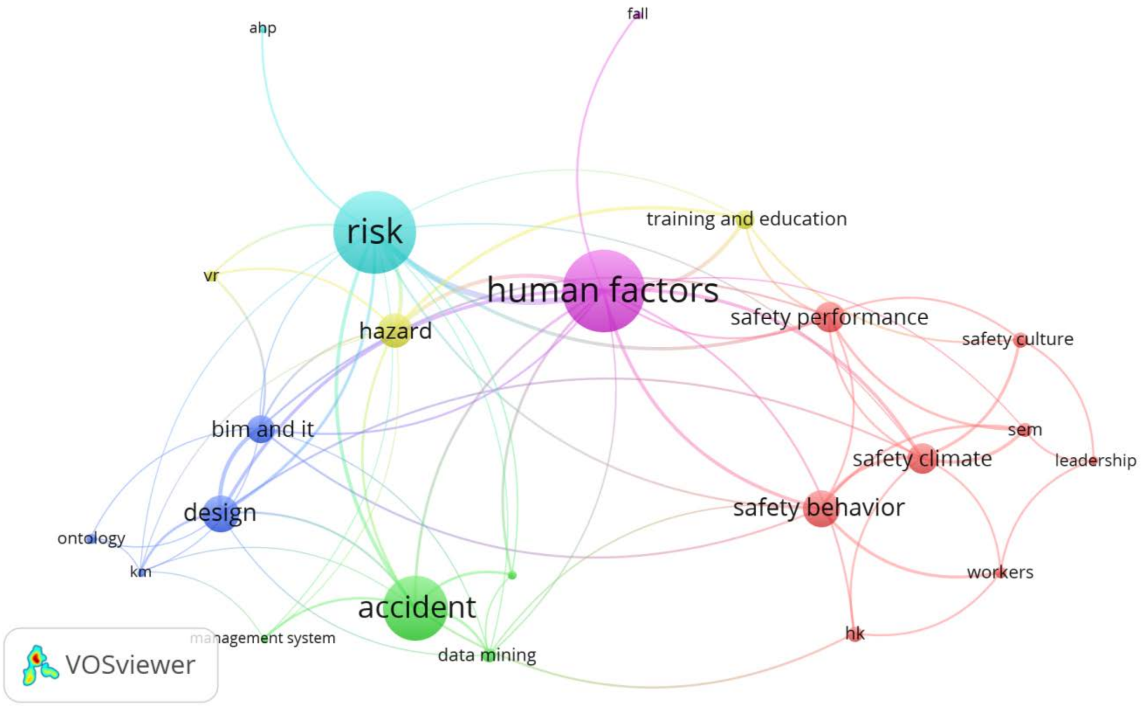


Fig.5. Visualization of author keywords from the literature sample published before 2009



Note: VR stands for virtual reality

Fig. 6. Visualization of author keywords from the literature sample published following 2009

3.4.Scholars in construction safety

Citation analysis was conducted using *VOSViewer*. In this study, a minimum number of documents and minimum citation number of a scholar were set at 5 and 30 respectively. As a result, a total of 35 scholars met the thresholds and visualized in Fig.7.

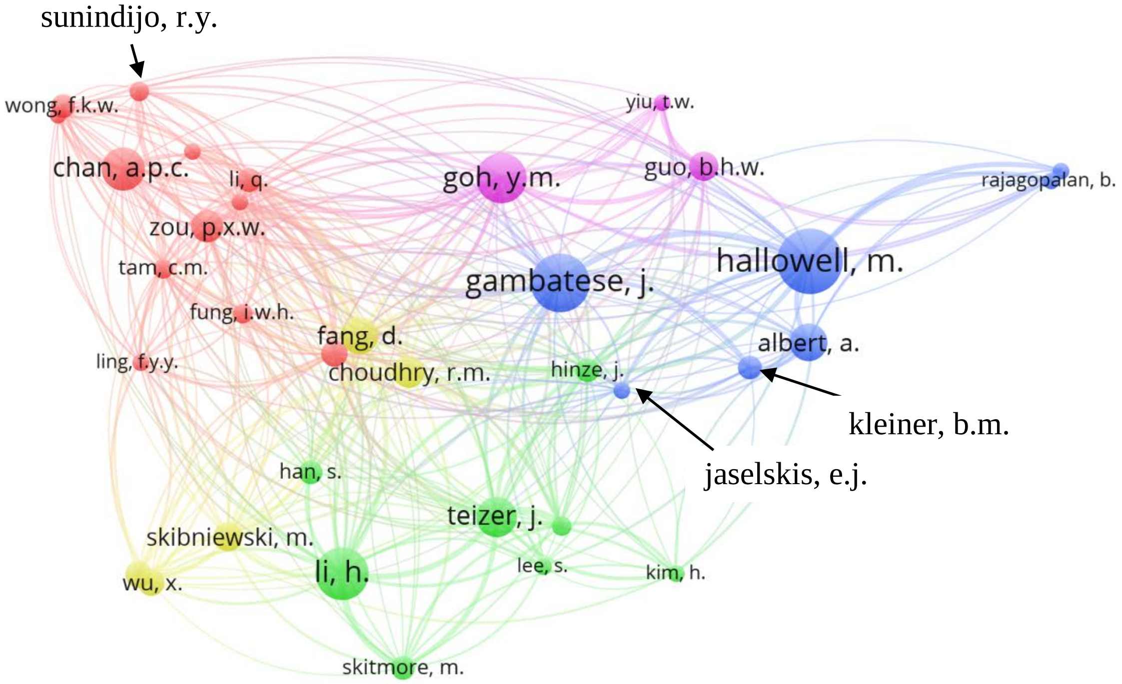


Fig.7. Visualization of scholars in the research community of construction safety

The font and circle size for each scholar indicate their number of publications in construction safety. Scholars displayed in Fig.7 were divided into different clusters according to their own citation networks. For example, Zou, P.X.W., Chan, A.P.C., Li,Q., Wong, F.K.W., Tam, C.M., Sunindijo, R.Y., Ling, F.Y.Y., and Fung, I.W.H occurred to be in the same cluster, indicating their mutual influence by citing each other’s work. The influence among scholars can be further measured by the distance and connection lines shown in Fig.7. For example, Fang, D. and Choudhry, R.M. can be found with strong linkage in construction safety research. The quantitative analysis of scholars’ academic influence is provided in Table 3.

Table 3. Quantitative summary of impacts of scholars in the academic community of construction safety

Scholar name	**Number of articles**	**Total citation**	**Norm. Citation**	**Ave. Pub. Yr.**	**Average citation**	**Ave. Norm. Citation**
Zhang, S.	6	334	22.56	2015	55.67	3.76
Teizer, J.	13	712	37.83	2013	54.77	2.91
Li, H.	17	148	38.40	2015	8.71	2.26
Lee, S.	5	100	11.06	2015	20.00	2.21

Yiu, T.W.	5	52	10.34	2016	10.40	2.07
Tam, C.M.	6	345	11.92	2004	57.50	1.99
Hinze, J.	7	449	13.84	2009	64.14	1.98
Tixier, A.J.-P.	5	53	9.87	2016	10.60	1.97
Fung, I.W.H.	6	204	11.42	2007	34.00	1.90
Rajagopalan, B.	5	44	9.43	2016	8.80	1.89
Jaselskis, E.J.	5	184	9.25	2003	36.80	1.85
Skitmore, M.	7	49	12.16	2016	7.00	1.74
Wu, X.	8	105	13.80	2016	13.13	1.73
Skibniewski, M.	9	128	15.05	2016	14.22	1.67
Zhou, Z.	5	98	8.32	2014	19.60	1.66
Zhang, L.	8	104	13.17	2016	13.00	1.65
Fang, D.	12	658	17.89	2012	54.83	1.49
Choudhry, R.M.	10	571	14.62	2011	57.10	1.46
Li, Q.	7	101	10.23	2015	14.43	1.46
Mohamed, S.	8	399	11.42	2010	49.88	1.43
Kim, H.	5	60	7.12	2015	12.00	1.42
Hallowell, M.	22	380	29.22	2015	17.27	1.33
Gambatese, J.	19	559	23.55	2012	29.42	1.24
Guo, B.H.W.	9	53	10.98	2017	5.89	1.22
Kleiner, B.M.	7	89	8.13	2015	12.71	1.16
Albert, A.	12	113	13.86	2016	9.42	1.16
Ling, F.Y.Y.	5	188	5.68	2010	37.60	1.14
Han, S.	7	89	7.16	2015	12.71	1.02
Goh, Y.M.	16	160	13.17	2015	10.00	0.82
Zou, P.X.W.	10	115	7.61	2014	11.50	0.76
Sunindijo, R.Y.	6	74	4.55	2013	12.33	0.76
Hon, C.K.H.	5	37	3.75	2016	7.40	0.75
Chan, A.P.C.	14	113	8.64	2013	8.07	0.62
Wong, F.K.W.	7	44	4.04	2013	6.29	0.58
Irizarry, J.	5	42	2.83	2014	8.40	0.57

Scholars listed in Table 3 are based on their Ave. Norm. Citation. It is seen in Table 3 that Zhang, S, although with only six articles in total from the literature sample, has the highest influence measured by the Ave. Norm. Citation. In terms of Norm. Citation representing the average citation per year of all personal publications, Teizer, J., Li, H., and Hallowell, M. top the table. In terms of total citation and average citation, Fang, D., Gambatese, J., Choudhry, R.M., and Hinze, J. can be considered scholars with the highest contribution to the academic community of construction safety. Hallowell, M., Gambatese, J.,Li, H., Goh, Y.M., and Chan, A.P.C. can be considered as most productive scholars measured by their number of publications in this literature sample. The Ave. Pub. Yr. infers the recentness of publications of the scholar. As seen in Table 3, most scholars remain active in the research domain of construction safety, except Tam, C.M., Fung, I.W.H., Jaselskis, E.J., and Hinze, J., whose values of Ave. Pub. Yr. are all before 2010.

3.5.Document analysis

Setting the minimum citation number at 50 in filtering the literature sample, a total of 49 articles met the requirements. These most influential articles in terms of normalized citation are listed in Table 4.

Table 4. Summary of highly cited journal articles in construction safety

Article	Title	Total citation	Normalized citation
Zhang et al., (2013)	Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules	201	9.82
Zhang et al. (2015b)	BIM-based fall hazard identification and prevention in construction safety planning	51	4.89
Teizer et al. (2010)	Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system	164	4.73
Hinze et al. (2013)	Leading indicators of construction safety performance	86	4.20
Mohamed (1999)	Empirical investigation of construction safety management activities and performance in Australia	53	4.08
Lee et al. (2012)	RFID-Based Real-Time Locating System for Construction Safety Management	55	4.07
Cheng and Teizer (2013)	Real-time resource location data collection and visualization technology for construction safety and activity monitoring applications	82	4.01
Choudhry et al. (2007)	The nature of safety culture: A survey of the state-of-the-art	222	3.85
Tam et al. (2002)	Non-structural fuzzy decision support system for evaluation of construction safety management system	63	3.53
Hallowell and Gambatese (2009)	Construction safety risk mitigation	80	3.33
Gürcanli and Müngen (2009)	An occupational safety risk analysis method at construction sites using fuzzy sets	79	3.29
Tam et al. (2004)	Identifying elements of poor construction safety management in China	167	3.27
(Carter and Smith, 2006)	Safety hazard identification on construction projects	144	2.97

(Behm, 2005)	Linking construction fatalities to the design for construction safety concept	172	2.94
Choudhry and Fang (2008)	Why operatives engage in unsafe work behavior: Investigating factors on construction sites	188	2.87
Pinto et al. (2011)	Occupational risk assessment in construction industry - Overview and reflection	82	2.66
Jaselskis et al. (1996)	Strategies for achieving excellence in construction safety performance	141	2.53
Gambatese et al. (1997)	Tool to design for construction worker safety	82	2.43
Garrett and Teizer (2009)	Human factors analysis classification system relating to human error awareness taxonomy in construction safety	54	2.25
Kartam (1997)	Integrating safety and health performance into construction CPM	76	2.25
Aksorn and Hadikusumo (2008)	Critical success factors influencing safety program performance in Thai construction projects	133	2.03

It should be noticed that not all filtered 49 articles are presented in Table 4 but only with normalized citation over 2.00. Other articles such as Gambatese et al. (2005) and Gambatese et al. (2008) although with high total citation, the normalized citation are below 2.00. The study of Zhang et al. (2013) focusing on BIM applied in automatic safety checking has received significantly higher normalized citation than the other articles. It is indicated from Table 4 that these most influential articles generally applied ICT (e.g., BIM and real-time data capturing) in safety management. Other articles representing more traditional safety research include safety culture (Choudhry et al., 2007), safety indicators (Hinze et al., 2013), safety behavior (Choudhry and Fang, 2008), hazard identification (Carter and Smith, 2006), risk assessment (Pinto et al., 2011), safety program and its critical factors (Aksorn and Hadikusumo, 2008), design for safety (Gambatese et al., 1997), and safety performance (Jaselskis et al., 1996).

4. Qualitative discussions

Following up the bibliometric analysis and science mapping of the selected literature sample, the in-depth qualitative discussion now focused on summarizing the main research topics within the theme of construction safety, identifying the existing research gaps, as well as proposing a framework by linking existing research topics into future recommended directions.

4.1.Summary of main research topics in construction safety

The seven main clusters of keywords identified from Fig.2 are not separated. Instead, keywords from different clusters could have strong links. For example, BIM and VR are both digital technology and are linked to each other to be applied in safety management, although VR is more commonly applied in safety education and training, while BIM can be more widely applied in various safety management activities such as design for safety and site planning (Choi et al., 2017; Malekitabar et al., 2016). Continued from the clustering of keywords in Section 3.2, the mainstream research topics in construction safety can be summarized below.

4.1.1. Safety climate and safety culture

There have been multiple studies focusing on developing, testing, and evaluating the framework of safety climate or safety culture (Ardeshir and Mohajeri, 2018; Chen et al., 2018), as well as linking them to safety performance measurement (Alruqi et al., 2018). Key indicators within safety climate (Alruqi et al., 2018; Newaz et al., 2018) is being kept updated and validated using statistical methods such as SEM (Zhang et al., 2018a). Commonly defined elements within safety climate include but are not limited to management commitment (Zahoor et al., 2017), co-workers caring and communication (Gao et al., 2016), and safety behavior (Zhang et al., 2017). A high attention within safety climate has been paid on workers, such as worker behavior (Jiang et al., 2018), safety compliance (Xia et al., 2018), and perceptions (Stiehl and Forst, 2018).

Multiple studies (Guldenmund, 2000; Marquardt et al., 2012) indicate that safety climate forms a core part of safety culture (Zou and Sunindijo 2015). Safety culture studies have been much focusing on the organization level (Goncalves Filho and Waterson, 2018), not just within contractors (Karakhan et al., 2018) but also other stakeholders(Wu et al., 2015a). Modeling safety culture can be found in various existing studies (Koch, 2013; Trinh et al., 2018). Much work (e.g., Choudhry et al., 2009; Wen Lim et al., 2018) has addressed the relationships among safety climate, safety culture, and safety performance. For example, Teo and Feng (2009) found that safety climate impacted safety culture in terms of psychological, situational/environmental and behavioral aspects, and the assessment of safety climate could predict safety culture, which could further influences safety performance (Choudhry et al., 2009).

4.1.2. Information and communication technology in safety management

Information and communication technologies (ICT) have been emerging in the global construction industry. BIM has displayed its role in safety management as showcased in existing studies (Chen and Liu, 2015; Zhang et al., 2015b), such as training for workers in off-site construction by increasing workers' hazard awareness (Li et al., 2015b), visualization of scaffolding and safety facilities for accident prevention (Liu et al., 2017), and developing databases of near-miss events on-site (Shen and Marks, 2016). Besides BIM, VR has shown its influence in safety training and education (Pedro et al., 2016), specifically in hazard recognition and risk identification in the virtual environment (Perlman et al., 2014) and improving the communication between designer and builder (Sacks et al., 2015). Multiple other digital tools or media such as sensor-based technology, 3S (GIS/GPS/RS) technology, radio frequency identification (RFID) as mentioned by Zhou et al. (2013) could be integrated to assist construction safety management. For example, Aguilar and Hewage (2013) developed a real-time safety indicator from a centralized safety database with ICT to assist site managers' site decision making; Cheng and Teizer (2013) applied real-time data collection, processing, and visualization through remote sensing and VR to monitor site safety condition; Zou et al. (2017a) developed a cloud-based safety information and communication system to improve road construction safety.

4.1.3. Workers' safety perception and behavior

Workers health and safety on construction sites have been largely focused when applying ICTs. For instance, Park et al. (2016) created and evaluated a proximity detection and alert system using Bluetooth sensing technology aiming to protect the health and safety of pavement workers; Yi and Wang (2017) applied a mixed-integer linear programming approach to optimize workers' site work schedule under hot outdoor weather condition; Workers' site condition exposed to unpleasant weather (e.g., hot temperature) has caught the attention of multiple researchers (Han et al., 2018; Yi and Chan, 2017). More studies have focused on workers' demographic or subgroup features, such as minority or immigration workers (Chan et al., 2017; Lyu et al., 2018; Suo and Zhang, 2017; Wasilkiewicz et al., 2016), workers from difference experience levels (Han et al., 2018), and workers from different building trades (Chen and Jin, 2015). The causes of workers' variation in their safety perception, attitudes, behavior, and performance have been linked to dimensions within safety climate such as safety awareness and co-workers attitudes (Choudhry and Fang, 2008), safety program (Bigelow et al., 1998), company size (Guo et al., 2018b), and management methods (Guo et al., 2018c). The causal connection analysis conducted by Winge et al. (2019) showed that supervision strongly affected workers' safety actions.

4.1.4. Safety management system

There is a significant correlation between management commitment and safety performance (Abudayyeh et al., 2006). An effective safety program incorporating the management commitment as well as training and education could ultimately lead to improved safety performance (Chen and Jin, 2012). Participation in safety management should not be limited to contractors, but other stakeholders such as the owner (Huang and Hinze, 2006). Researchers have been working on developing a safety management plan that a typical contractor can adopt (Shahbodaghlou and Haven, 2000). Key factors within safety management program have been studied to explore their inter-relationships. For instance, Bavafa et al. (2018) found that safety commitment and responsibilities, subcontractors and personnel's selection, safety supervisor and professionals, plan for safety, and employee involvement were key critical factors to have an improved safety program. Similarly, a total of 16 critical factors influencing the success of a construction safety program was identified and tested by Aksorn and Hadikusumo (2008). Similar studies investigating key factors for effective implementation of safety management system can be found in Pereira et al. (2018) and Yiu et al. (2018). The subcontracting nature of the construction industry indicates that an effective safety program should gain the joint-effort among multiple organizations to maintain consistent safety compliance, which could be evaluated based on behavior-based safety rules (Guo et al., 2018a). The conflicting objective between site productivity and safety as indicated by Sandberg and Albrechtsen (2018) needs to be properly handled in the safety reporting process, which should be part of an effective management program.

4.1.5. Hazard identification, accident causation, and risk management in safety

(Pereira et al., 2018) found that the highest-priority accident precursors are workers' failure to identify hazards and negligence of hazards. Hazard identification, accident investigation, and risk assessment have been a long-standing research topics within construction safety management. Earlier studies have been focusing on proper protective equipment (Lette et al., 2018), accident types and physical barrier elements (Winge and Albrechtsen, 2018), causes of accidents or incidents (Ale et al., 2008; Haslam et al., 2005; Manu et al., 2010), safety training (Jeelani et al., 2018), and effective management program (Li et al., 2018b). More recent studies (Choe and Leite, 2017; Malekitabar et al., 2016; Park et al., 2017; Yi et al., 2015; Zou et al., 2017b) have been emphasizing on ICT (e.g., BIM) as the digital approach in mitigating safety risks. Safety should be considered in the design stage (Teo et al., 2016), when hazards can be identified in the ontology-based semantic modeling (Zhang et al., 2015a).

4.2.Research gaps in construction safety

4.2.1. An adaptable safety climate and safety culture framework

The scale of safety climate research cross different levels, including industry, organization, site, and group levels (Chen et al., 2018). An adaptable or robust safety climate indicator system that can be applied in different sites or groups could be further developed, due to the heterogeneous features and complexity of construction projects. Similarly, Trinh et al. (2018) indicated that a resilient safety culture model should lead to high safety performance regardless of the changing complexity levels or conditions of construction projects. There is a gap of how such an indicator system in safety climate and the safety culture model can be more widely applicable in inter-organizational context and also in different project sites and subgroups of site employees. The indicators within safety climate and culture are not completely consistent among studies (Li et al., 2017; McCabe et al., 2017; Wu et al., 2015b), possibly due to the general safety culture in the industry level within a country or region's context. Most existing studies (Chen et al., 2013; Zahoor et al., 2017) on safety climate and safety culture have been set on the context of a specific country, with limited extending the framework for cross-country validation or international comparison. Nevertheless, it is an important issue of implementing safety practice in international construction projects (Gao et al., 2018) and sharing the safety experience crossing countries (Gibb et al., 2014).

4.2.2. ICT application in construction safety

A review of these studies applying ICT in site safety indicates that most studies have focused on fall hazard identification (Melzner et al., 2013; Qi et al., 2014; Wang et al., 2015; Zhang et al., 2015b). As there are multiple common hazards on construction sites, such as fall, struck-by, caught-in-between, and electrocution identified as Focus4Hazard by (OSHA, 2011). More ICT-based platforms, prototypes, or user interfaces could be extended to incorporate these main hazards on-site. A step forward of the existing research in applying BIM for safety hazard identification could be to create a prototype that automatically updates hazard assessment the as-planned BIM as project progresses. Hazard assessment is defined as the occurrence, severity, and risk level according to existing safety database. More importantly, the established ICT-based prototype or frameworks (Teo et al., 2016) could be further tested with more real-world cases, including its user friendliness, users' readiness, acceptance, and easiness for safety communication. From the technical perspective, the interoperability among multiple ICT tools (e.g., BIM and wireless sensing) to allow information exchange during real-time data collection and processing needs to be further studied.

4.2.3. Workers' safety issues

Subgroup factors of workers (e.g., age and site experience level) could cause different safety perceptions (Han et al., 2018), further leading to varied safety behavior (Li et al., 2015c), and ultimately safety performance (Chen et al., 2018). Besides these internal influence factors, there have been limited studies of how the external conditions of jobsites (e.g., lighting, temperature, spatial crowdedness) affect workers safety perception, behavior, and performance. Workers' safety perceptions towards site hazards and risks could be further linked to their safety cognition pattern (Liu, 2018; Marquardt et al., 2012). There have been limited studies linking their cognition patterns (e.g., safety knowledge-based, prior scenario-based, and basic assumption-based) into safety perceptions. Furthermore, the cognition psychology or cognitive model, although having been studied in other industries or fields such as traffic (Aksan et al., 2017; Lyu et al., 2017), have not been sufficiently applied in construction safety, especially in workers' safety perception or behavior (Fang et al., 2016).

4.2.4. Adaptability of safety management system

Similar to the studies in safety climate and safety culture, the effectiveness of existing safety programs should also be tested in different organization sizes, different project conditions, and different country contexts as indicated by Bavafa et al. (2018) and Oswald et al. (2018). More recent studies (Kim et al., 2019) have proposed ICT (e.g., Internet-of-Things) in safety management. However, many of these studies stay in the framework stage, more solid work needs to be conducted in the future to establish, test, validate, and finally apply the proposed ICT-based safety management programs. The longer-term effects of specific safety programs on safety climate and safety performance could be further investigated (Jeschke et al., 2017). The latest research by Niu et al. (2018) proposed the artificial intelligence that harnesses the power of smart features within the newly developed system, which was named as the “third wave” construction safety management, following “first wave” of safety management focusing on “hard” equipment and the “second wave” highlighting the “soft” managerial safety (e.g., safety culture).

4.2.5. Hazard recognition and risk mitigation

Generally speaking, safety research in hazard recognition and risk mitigation could be categorized as managerial studies which focus on human factors (e.g., workers’ characteristics) and information technologies (e.g., BIM). There have been more emerging studies by applying ICT tools in safety hazard identification and risk assessment such as (Qi et al., 2014) and (Yi et al., 2015). Digital technologies such as BIM and VR are being applied in the pre-construction stage to enhance workers’ skills in identifying and assessing hazards. However, there have been insufficient studies in integrating ICT to monitor workers’ safety behavior and update it for safety managers. It is known that ICT could assist design for safety in pre-construction stages. As the construction project progresses, there could be updated BIM model by incorporating workers’ latest activities through site data collected by wireless sensing technologies. Therefore, safety managers are kept updated with workers’ physical status and work progress. Safety managers can also be informed of potential hazards that might hold workers at risk as workers’ tasks change or the project progresses. More future work can be performed in bridging the manager monitoring of workers’ safety and workers’ own self-awareness of safety hazards through ICT tools. Besides the technological innovation, the readiness of workers and management personnel to adopt newly developed ICT platforms should also be considered.

4.3.Research trends in construction safety

Based on the keyword analysis, qualitative discussions of mainstream research areas within construction, as well as gap analysis, a research framework suggesting future directions is proposed in Fig.8.

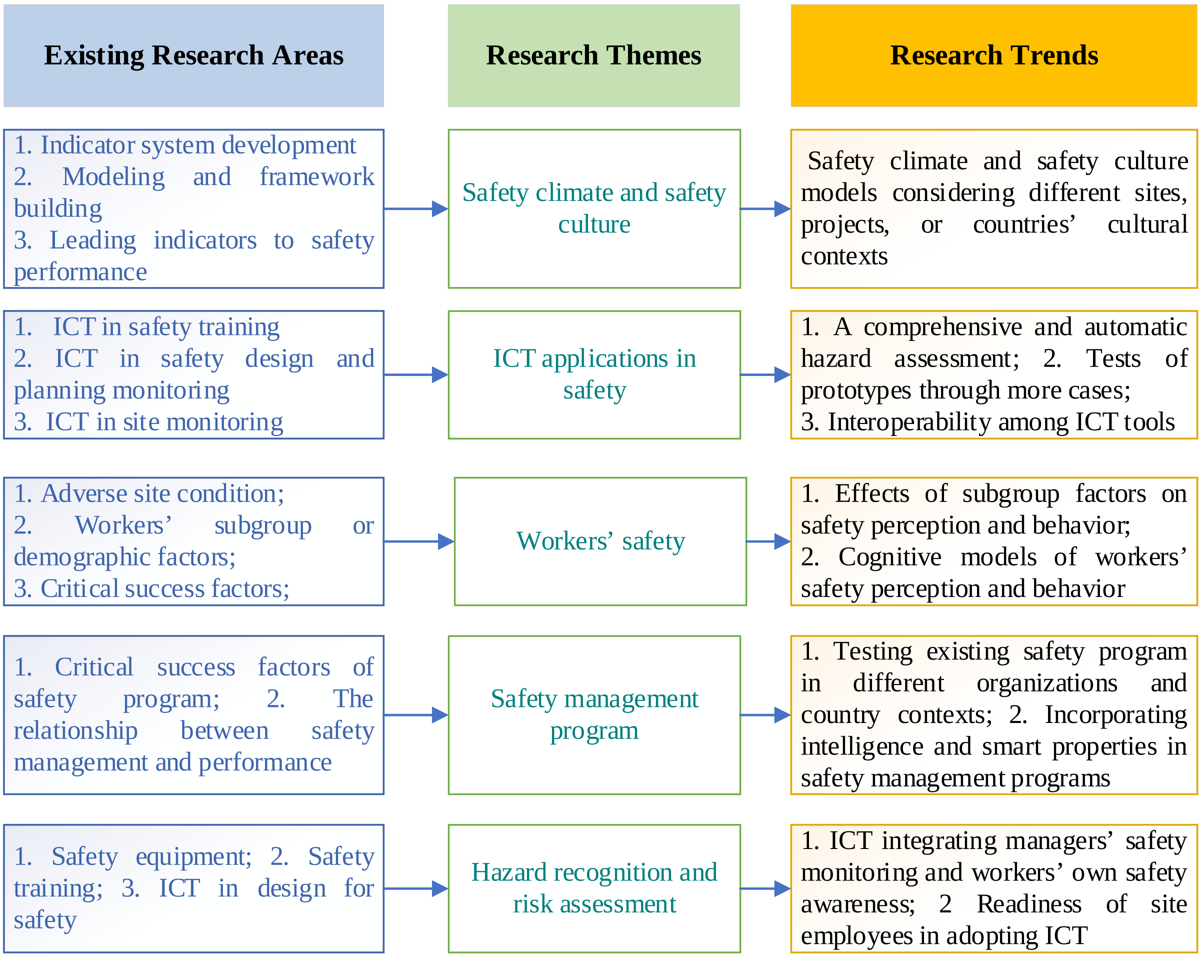


Fig.8. Research framework linking existing studies areas in construction safety to future directions

It should be noticed that these research themes shown in Fig.8 are not separated, but closely inter-connected. For example, ICT has gaining its momentum in being applied in safety management program and risk management; workers' safety forms a core part of safety climate; and workers' safety perceptions are driven by their hazard recognition and risk assessments. A few directions in the future study of construction safety domain can be foreseen, including:

1. Updated safety climate indicator systems and safety culture models that are either cross-cultural, inter-organizational, or incorporating different levels of project complexity or site conditions;
2. Integration of artificial intelligence, data analytics, and multiple ICT tools (e.g., BIM and VR) in safety planning, site monitoring, and decision making;
3. Interdisciplinary approach addressing workers health and safety especially unpleasant physical condition(Yi and Wang, 2017);
4. Tests of cognition models of workers' safety perception and behaviors incorporating their subgroup or demographic factors;
5. Smart construction site safety management enabling an effective coordination and communication between workers of different trades and management personnel;
6. User-friendly and site-ready risk management tools applying ICT.

Besides these above-mentioned emerging research directions in construction safety research, safety compliance and rule-checking could be studied in a different context such as off-site construction which is an emerging alternative construction technique that shortening the in-site construction period (Jin et al., 2018).

5. Conclusions

This study adopted a science mapping approach consisting of bibliometric search and scientometric analysis followed by an in-depth qualitative discussion to review over 500 journal articles in the domain of construction safety. It was found that over the past decade, there had been significant increasing publications in construction safety, especially since 2012. It could be further indicated that construction safety is a traditional and everlasting research domain that is being kept updated with new elements (e.g., IT, BIM, VR). Journals that have been productive in publishing construction safety were identified to be *Journal of Construction Engineering and Management*, *Safety Science, and Automation in Construction.* Keyword analysis revealed the mainstream topics within this domain, including accident prevention, human factors, risk assessment, safety climate, safety behaviour, BIM and information technology, and hazard identification. By further dividing the literature sample into two subsamples according to their year of publications, it was found that studies within the recent decade had paid more attention on applying digital information technologies especially BIM in safety management. Other relevant topics had also become popular, including virtual reality, ontology, data mining, and analytic hierarchy process. Several keywords have a longer history but remain ongoing research themes, including human factors (e.g., safety behaviour), safety performance, safety climate, training and safety program, risk assessment, and perceptions. The scientometric analysis provided insights for the future research directions, such as applying digital information technologies and data analytics in safety management, as well as further studying how BIM affects design for safety, site monitoring, workers' safety behaviour, and ultimately the safety performance.

Applying the same quantitative measurements (e.g., normalized citation), the influence of journals, keywords, scholars, and articles were clustered and analysed, and it is found that simulation and fall from height were the top keywords that received the highest normalized citation, indicating that the academic community had paid more attention on applying simulation techniques in safety planning, as well as commonly encountered hazards such as fall. Leading indicator is another influential keyword, meaning that proactive measurement such as safety climate is an ongoing highly studied topic. It is also found that most productive scholars in construction safety were identified according to the selected literature sample, including Hallowell, M., Gambatese, J., Li, H., Goh, Y.M., and Chan, A.P.C. Other than that Zhang, S, although not with the highest number of publication, was found with highest influence in construction safety by applying BIM in safety management; In addition, the most influential articles in construction safety were found related to BIM or other information technologies (e.g., real-time data capturing), although traditional topics within construction safety such as safety program and safety behaviour remained popular in the academic community.

1. The in-depth qualitative discussion revealed that future research directions could be in the following six areas: an adaptable safety climate and safety culture model by incorporating contexts in different sites, project complexity levels, or countries;
2. extending established prototypes of applying information technologies to a wider construction community through more tests and case studies;
3. continuing studies of subgroups factors linked to cognitive models of workers' safety perception and behaviour;
4. incorporating artificial intelligence and smart properties into safety program management;
5. developing and applying information technologies that could enhance the safety communication and coordination between management personnel and workers;
6. evaluating the user acceptance and industry readiness of applying various information technologies in construction safety management.

These proposed directions for future work could benefit both academic community and industry practitioners in enhancing safety performance and improving site employees' health and wellbeing. It should be pointed out that the current review is limited to the selected literature sample published in *Scopus* and only English journal articles were included. It might have potentially excluded some latest studies published in other languages or other types of documents such as trade magazines.

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