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Design for safety (DfS) practice in construction engineering and management research: A review of current trends and future directions

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ABSTRACT

For past decades, design for safety (DfS) has gained growing interest among scholars and practitioners in different geographical contexts as one of the innovative practices integrating worker health and safety in the front-end of the project lifecycle. However, a systematic scientometric study appraising the research development in DfS practice in construction domain remains elusive. This paper aims to bridge this gap by conducting a scientometric review of the available DfS literature in the construction domain. A total of 167 relevant articles were retrieved using a systematic data acquisition approach from Scopus and snowballing and then put forward into a scientometric analysis to construct science maps. The scientometric review identifies the most prolific journals, authorship, cooccurrence network of keywords, article citations, and regions. An in-depth qualitative discussion is presented to provide deeper insights into the existing studies and opportunities for future research in five main DfS research themes as follows: (1) DfS concept and management; (2) DfS technological advancement; (3) DfS capability and competency; (4) DfS education; and (5) DfS sustainability. The value and uniqueness of this review study lie in its novel contribution to the body of DfS knowledge through synthesizing the wider DfS literature landscape in the construction domain. The findings offer a point of reference for both academia and industry in bridging the deficiencies in the current research and providing pathways for future directions in DfS research.

1. Introduction

The Design for Safety (DfS) concept is one of the innovative hazard prevention strategies for reducing and eliminating associated fatal and non-fatal occupational injuries [1,2]. The idea of this concept originated from two theories; The theory that construction accidents result from attributes of facility design as described by Lorent's 1987 report and [3] Time-Safety Influence Curve theory [4]. These theories were further developed by several scholars to strengthen the ethos of collective responsibilities in minimizing the occupational safety and health (OSH) risks upstream of the chain [5,6].

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DfS adoption rates in different geographical contexts (e.g., the UK, the U.S, South Africa, Australia, Singapore, Malaysia, Korea) have grown quite considerably in the past several years [7]. In particular, the introduction of Council Directive (CD) 92/57/EEC in 1992 has led the European and other regions to transpose the CD 92/57/EEC diligently into the national DfS-related legislations. For example, UK has incorporated DfS into the Construction (Design and Management) Regulations 2015 (CDM 2015) (which was originally introduced in 1995 and subsequently revised in 2007). Similarly, the Nordic countries have highlighted the importance of OSH responsibilities, safety and health coordination for design and construction phases and documents in hazard prevention in their respective legislative frameworks such as in Executive Order no. 117 (Denmark), Safety of Construction Work (205/2009) (Finland) and Building and Civil Engineering Work (AFS. 1999:3) (Sweden). Other regions, such as Asia, Africa, and Oceania, are also seeing the adoption of DfS-related legislation and guidance (see Fig. 1). While most countries have mandated DfS practices, countries such as the United States, Malaysia, and Hong Kong continue to implement DfS voluntarily.

Given the institutional pressures for DfS legislation, as well as its theoretical and practical implications, DfS practice has attracted considerable attention from scholars and practitioners, resulting in an increase in DfS publications. Scholars initially focused on the concept (Hinze, 2000; [5], viability [8]; Weinstein et al., 2005), barriers [9], and role of designers [10]. With the further development of studies, several scholars have shifted the focus to financial implications [11], education [12], digital technologies (e.g. Building Information Modelling (BIM)) [13], stakeholder's knowledge, attitude and practice [7,14], DfS implementation factors [15] and capability [1,16,17]. Despite the fact that DfS research has been ongoing in recent years, the vast amount of research now available makes it difficult to evaluate the exact dimension of the knowledge discovered, its critical domains, and emerging trends. Although there are several review studies related to construction safety (see Refs. [18,19,20], the findings have tended to focus primarily on the general context of construction safety (e.g., safety culture, safety management, safety climate, safety technologies). Such an exercise on DfS is important to provide a point of reference for guide scholars and practitioners to enable mainstreaming of DfS knowledge and practice [21].

To address the above-mentioned deficiency, this study aims to identify the current research status and provide insights into future research directions of DfS in construction through the science mapping (i.e., scientometric) analysis approach. The use of scientometric approach is considered appropriate as it can facilitate a more comprehensive review and quantitative approach to provide in-depth and comprehensive understanding of current and emerging research areas in a specific subject (i.e., DfS in construction) [22]; Li et al., 2017). Furthermore, despite scientometric analysis approach has been successfully adopted in the field of OSH in construction such as BIM in construction safety [23], fall from height research in construction [24], health and safety of women in construction [25] and personal protective equipment (PPE) in construction [26], the aforementioned studies mainly focused on reviewing different aspects of construction safety and little, if any, of such analysis has been performed to capture the insight on the DfS construction. It is worth noting that although [27] conducted a narrative review study related to DfS concept, the search was limited to the evidence and theory related to the understanding of construction hazards based on qualitative and objective technological platforms. The study above provides a useful theoretical basis to understand the potential evidence-based methods to address the gaps in construction hazards in DfS practice. Furthermore, while [1,28,7] reviewed the DfS concept, these studies focused on one specific dimension of DfS (i.e., designer and organisational capability) rather than the entire concept of DfS. On the other hand, although [29] in their recent study focused on systematic literature review of PtD, their study mainly focused on a wide range of digital technologies for enhancing PtD. Also, despite a recent study by Ref. [30] conducted a review on DfS, their focus was mainly on reviewing the application of DfS (based on the limited number of 16 articles) specific to the construction industry of developing countries. The study, from which this paper is

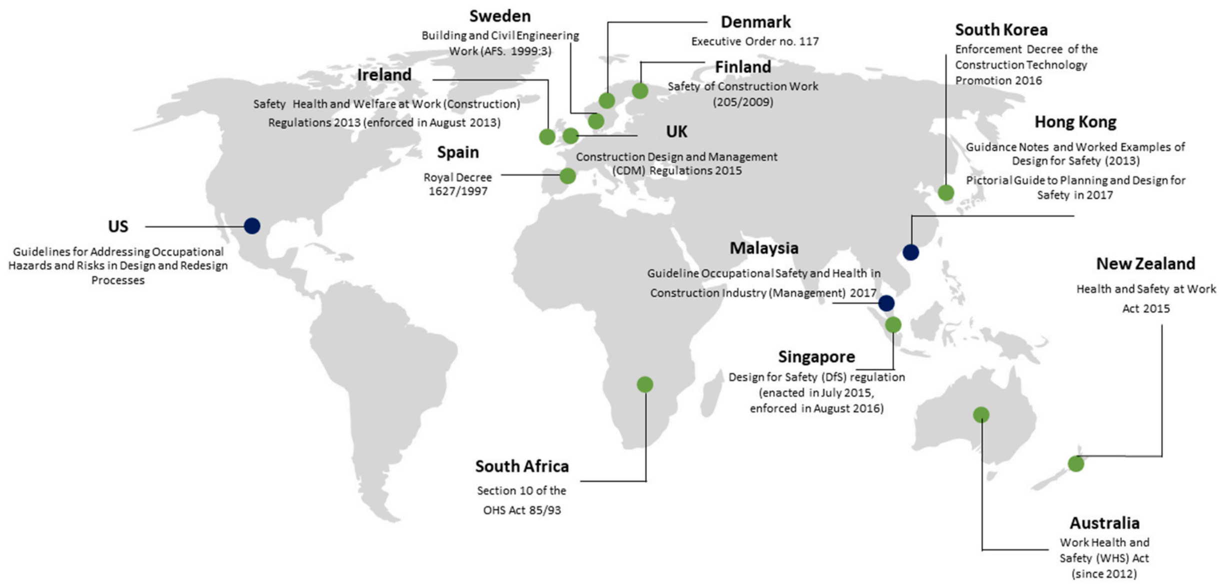

Fig. 1. Mapping of examples of DfS-related legislation and guidance around the globe.

developed takes a holistic approach based on the wider DfS dimensions in the construction literature. Thus, the purposes of this scientometric review study are as follows: (1) to summarize the trends in DfS research in the field of construction; (2) to determine DfS research status from the perspective of a co-occurrence network; and (3) to identify DfS research themes through cluster analysis as a future research roadmap. This scientometric review article is structured as follows: the next section describes the research methodology. The collected articles are then examined in five ways: published journals, article citations, co-authorship, countries, and co-occurring keywords. Following the scientometric analysis, five main research themes are discussed (i.e., DfS concept and management, DfS technological advancement, DfS capability and competency, DfS education, and DfS sustainability). Future research

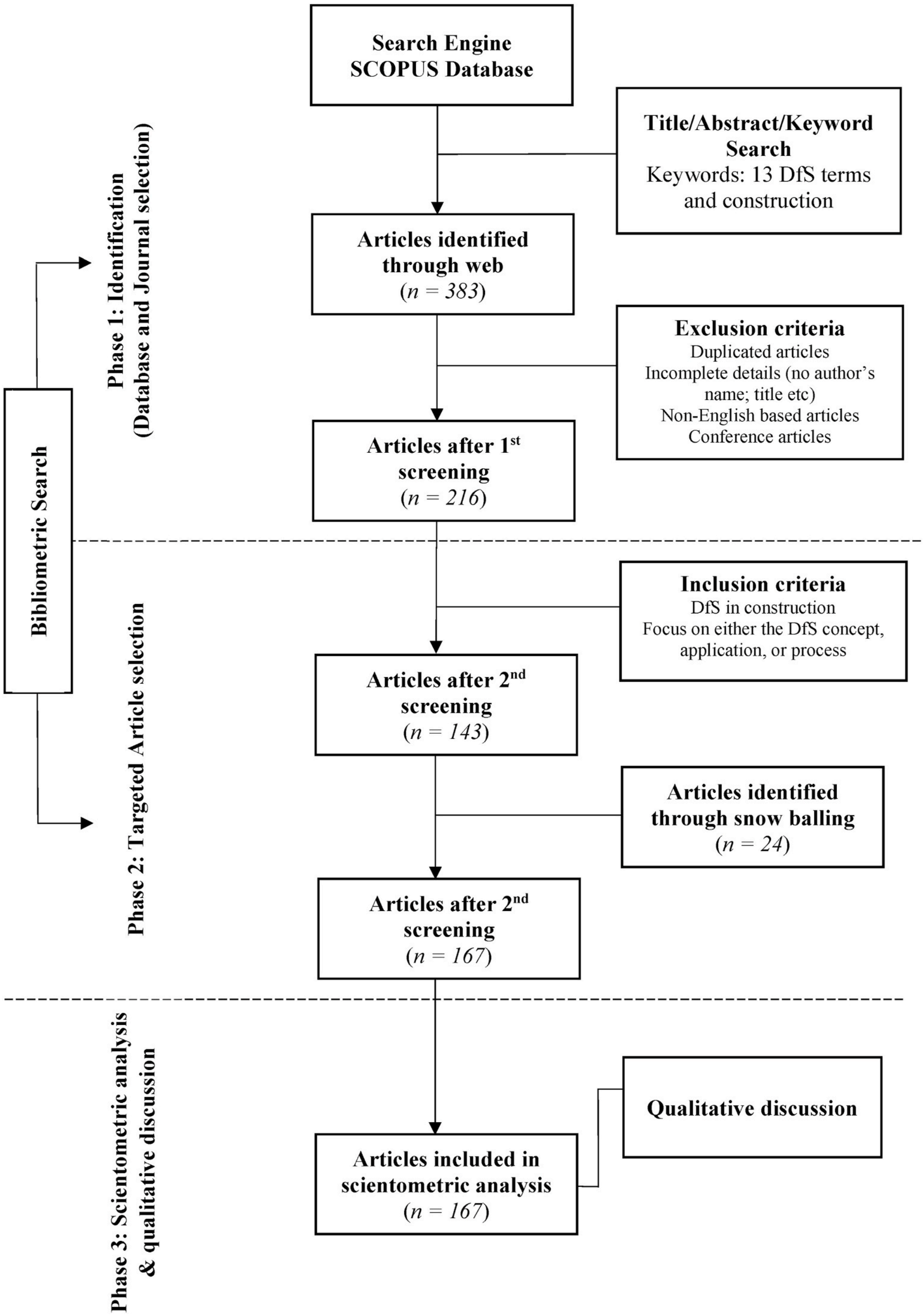

Fig. 2. A three-phase process in the review of DfS-based research in construction.

directions are proposed based on the discussion. Finally, at the end of this paper, there is a conclusion section.

2. Research methodology

This study adopted a three-step literature review approach by Ref. [31] (i.e., identification of database and journal, selection of target articles, and examination of the target articles via scientometric approach) summarizing the DfS research in the construction domain. A framework of this approach is illustrated in Fig. 2.

2.1. Phase 1: Identification of journal

Phase 1 of the bibliometric search was conducted through the SCOPUS database due to its size compared to other databases (e.g., Web of Science or Google Scholar) (Aghaei et al., 2017). Also, compared to other databases, Scopus has a broader range of multidisciplinary articles coverage, comprehensive bibliometric data, and a greater ability to access recently published papers [32]. The "Scopus" search engine was used to perform the search via "titles/abstract/keyword" based on keywords of DfS related terminologies and construction. To demonstrate the level of attention on the DfS subject in the construction engineering and management (CEM) research, the DfS related keywords were referred from previous DfS related studies in construction context (See Ref. [7]. The complete search string is listed as follows:

TITLE-ABS-KEY ("Prevention through Design" OR " Design for Safety" OR " Safety in Design" OR "Construction Design and Management" OR "Safety by Design" OR "Design for Construction Safety" OR "Design risk management" OR "Construction Hazards Prevention through Design" OR "Occupational Safety and Health in Construction Industry (Management)" OR "OSHCIM" OR "DfCWS" OR "DfCS" OR "CHPtD" AND "Construction")

The data for this study were retrieved from the SCOPUS database on February 6, 2022, and covers articles published from 1974 until 2022. Initially, 383 documents were found, and further screening was carried out to exclude articles that have duplications, incomplete details, non-English language and book chapters, conference publications (See Table 1). Conference articles were excluded from the sample due to limited information published in such publications [19,24], and also conference articles tend to be subsequently published in journals with greater depth of information. The initial screening in Phase 1 returned 216 articles from 98 different publications outlets.

2.2. Phase 2: Targeted article

In Phase 2, the 216 articles were subjected to a more thorough screening. The following inclusion criteria were used to ensure the relevance of the articles: the article should be specifically related to DfS practices in the construction industry; and the article should focus at least on either the concept, application, or process of DfS in construction. Any article that focuses on the context of construction safety (e.g., safety culture, safety management, safety climate, safety technologies) but does not fully emphasise the DfS was excluded. The keywords, abstract, and title of the article, as well as the content of the article (if necessary), were examined to ensure that the articles met the criteria. Publications that did not fall within the scope of the study (see exclusion criteria in Table 1) were excluded. Following the Phase 2 screening, the number of relevant articles was reduced to 143.

Furthermore, the snowball method was used to identify relevant articles that were not captured by the keywords in the Scopus database as well as outside the database, resulting in an additional 24 articles from journals. This exercise was carried out to supplement the findings of the first two-phase search, and hence ensuring any significant state-of-the-art works related to DfS studies were included for the reviewing exercise [16,33]. Finally, a total of 167 articles from 54 different journals were selected for the scientometric analysis.

2.3. Phase 3: Scientometric analysis

This review study used the science mapping analysis tool VOSViewer developed by Ref. [34] to conduct the scientometric analysis of the 167 articles. VOSViewer is designed for the construction and visualisation of bibliometric networks based on co-citation, bibliographic coupling, or co-authorship relations from a corpus of scientific literature (from common databased e.g., SCOPUS), with journals, researchers, or individual publications as actors [35,34]. The application of VOSViewer in scientometric analysis can be found in other recent science mapping-based studies in CEM domain, such as BIM [36], system dynamics [37], industry 4.0 [38] and robotics and automation [39]. Thus, this study adopted VOSViewer for scientometric analysis in visualizing, and analysing the influence of authors, countries, organisations, keywords, sources of documents in the field of DfS research in the construction industry.

Table 1
The exclusion criteria for screening exercise in bibliometric search.

Phase	Exclusion criteria	No. of articles
1	Duplication	3
	Incomplete details	12
	Non-English articles	10
	Italy (1); Spain (3); South Korea (2); China (4)	
	Conference publications	123
	Chapters in Book	17
2	DfS practices but not in construction domain (e.g., medical, manufacturing etc)	30
	Related to structural and material	9
	General construction OSH or other subject (e.g., education, accidents, equipments, lean) in construction and other sectors	33

Following the scientometric analysis, the qualitative analysis was conducted to provide detailed insight of the DfS community's mainstream research areas, gaps/limitations in current research, and proposed future studies in DfS in construction.

3. Results and discussion

3.1. Publication and growth trend

The 167 published articles were first summarized based on their year of publication. Fig. 3 depicts the annual publication distribution from 1974 to 2022. As shown in Fig. 3, less research was conducted on DfS in construction between 1984 and 2003. Some of the publications within this period were attributed to the introduction of CDM in 1994 in the UK. A rise is evident in 2008 with ten publications as compared to average of two publications observed in previous years. Given that most publications in 2008 came from the United States (US), the increase in publications may be due to a national initiative on DfS launched by the US National Institute of Occupational Health and Safety (NIOSH) with the goal of promoting the DfS philosophy, practice, and policy. A significant increase in DfS research in construction can be found in 2015 when the DfS subject drew more scholars from various geographical locations (e.g., Spain, Australia, UAE). The increased number of publications may be related to increased interest in the UK CDM revision in 2015. Despite a downward trend in publications from 2016 to 2018, broader dimensions of the DfS context were discovered, particularly in the context of DfS education, DfS resources, DfS motivation, DfS implementation factors, and DfS knowledge, attitude, and practices. Furthermore, the implementation of DfS regulations in Singapore in 2016 aided the increased number of DfS research in the Asian region. From 2019 onwards, there is a growing trend among the scholars from developing countries such as Nigeria [40,41], Ghana [42], Malaysia [7,43], and Palestine [44] focusing the readiness of the construction stakeholders, designers' capabilities and education. In addition, the revival of interest was seen in DfS application and automation, particularly the integration of Building Information Modelling (BIM) in DfS practices. Despite the trend showing inconsistencies (increase and decrease) in DfS research interest, the 83 published articles in the last six years account for 49.7% of the total articles. This provides evidence that the interest in DfS is growing among construction scholars and practitioners.

3.2. DfS publication sources

The 167 extracted publications were published in 54 different journals out of which 32 have only one publication within the assessed time frame. Table 2 presents the number of published articles on DfS in construction published by journals, including only journals that published three or more articles. *Safety Science* has the most publications with 22 publications and 1121 citations. This is followed by *Journal of Construction Engineering and Management* and *Automation in Construction* with 18 and 11 articles, respectively. This is supported by the citation analysis (See Fig. 4) where these three journals have the largest nodes.

Upon further analysis of the publication sources (see Fig. 4), it was found that there are significant information flow (via citations) between the sources where articles were published in highly specialised and high-impact journals in the safety and multidisciplinary construction research. In particular, the flow of information starts from *Safety Science* with a total link strength of 181, far exceeding that of any other journals. The *Journal of Construction Engineering and Management* came in second with a total link strength of 107, and *Automation in Construction* came in third with a total link strength of 74. Furthermore, the strongest collaboration is between *Safety Science* and *Journal of Construction Engineering and Management* with a link strength of 47, followed by *Safety Science* and *Automation in Construction* with a link strength of 29.

3.3. Most cited DfS publications

Table 3 shows that nine of the 167 extracted articles have been cited at least 100 times and over. As shown in Table 3, the majority of these publications focused on the fundamentals of DfS and automation, specifically the integration of BIM and DfS. Furthermore, the majority of BIM-related studies were simulation-based and case studies, whereas the fundamental studies used a mixed methodology. From the findings, the high interest in DfS research over the last decade has been mostly related to the domain of information technologies. One of the possible reasons was technological advancements, specifically BIM, which has the capability of facilitating visualisation and coordination in a broader dimension of safety management system, behavior-based safety, and safety culture [45].

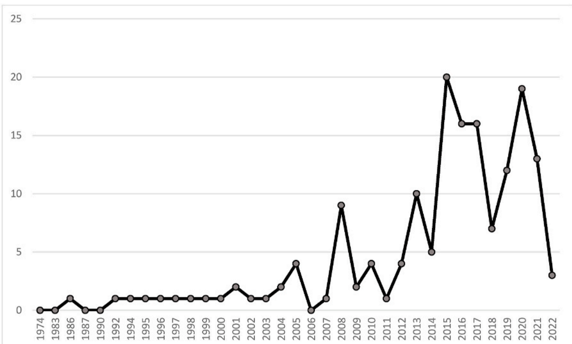

Fig. 3. The annual distribution of journal articles on DfS in construction.

Table 2
Top-14 journals that have published DfS related articles in construction domain.

No.	Journal	Cite Score 2020	No. of published articles	Total Citation
1	Safety Science	7.8	23	1121
2	Journal of Construction Engineering and Management	6.4	18	803
3	Automation in Construction	12.0	11	965
4	Journal of Safety Research	5.0	8	327
5	Journal of Professional Issues in Engineering Education and Practice (*changed to Journal of Civil Engineering Education in 2020)	3.7	8	195
6	Construction Management and Economics	5.6	8	201
7	Engineering, Construction and Architectural Management	4.0	8	96
8	Proceedings of the Institution of Civil Engineers: Civil Engineering	2.4	7	35
9	Architectural Engineering and Design Management	3.9	6	65
10	Practice Periodical on Structural Design and Construction	1.6	6	44
11	Journal of Architectural Engineering	2.3	5	231
12	Professional Safety	N/A	5	48
13	Accident Analysis and Prevention	7.8	3	77
14	Applied Sciences (Switzerland)	3.0	3	16

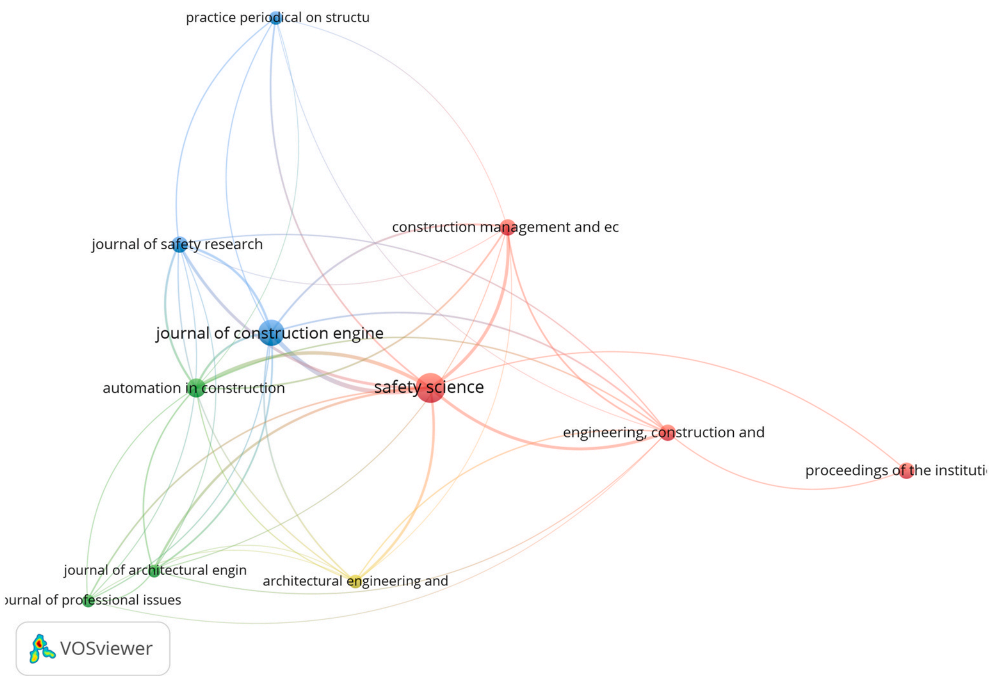

Fig. 4. Science mapping of published journals.

3.4. DfS publication per co-authorship network

Table 4 displays the results of the most active (with at least five articles) DfS researchers in the construction domain. The total strength of citation links between active authors and other researchers is also shown in the table. Eleven authors out of a total of 263 who have published DfS-related articles met the criteria. Among the 11 authors, Gambatese, J.A., of Oregon State University's School of Civil and Construction Engineering, has been the most active researcher (23 articles, 967 citations) in the DfS field. Other active researchers include Behm, M., Manu, P., and Toole, T. M. from East Carolina University in the US, The University of Manchester in the United Kingdom, and Bucknell University in the US, respectively. In addition, both Behm, M., and Manu, P. have connections to other authors in both developed and developing countries.

The author co-authorship density visualisation map network showing the collaboration of researchers is illustrated in Fig. 5. The generated map shows a cluster of four researchers that is well connected, with two clusters from the United States, one from the United Kingdom, and one from Malaysia. It is worth noting that a scholar, Behm, M., was discovered to be a key scholar in connecting researchers from different parts of the world, primarily between the United States and the United Kingdom. The density map (via overlay visualisation) also reveals that the majority of recent DfS research (for the past three years) have come from authors in the United Kingdom and Malaysia, with a focus on the DfS landscape in developing countries. The first group was led by Manu, P. from the United

Table 3
Most cited DfS publications.

Author (s)	Title of the article	Journal	Citations	Method	Focus
[46]	Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules	Automation in Construction	488	Simulation & Case studies	Integration Safety and BIM
[5]	Linking construction fatalities to the design for construction safety concept	Safety Science	288	Analysis of fatalities report	Concept
[13]	BIM-based fall hazard identification and prevention in construction safety planning	Safety Science	223	Simulation & Case studies	Integration Safety and BIM
[10]	Design's role in construction accident causality and prevention: Perspectives from an expert panel	Safety Science	185	Structured survey (email)	Role of designer
[47]	Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA)	Automation in Construction	192	Simulation & Interview	Automation
[8]	Viability of designing for construction worker safety	Journal of Construction Eng. and Mgmnt	153	Structured survey (interview)	Concept
[48]	Role of designers in construction worker safety	Journal of Construction Eng. and Mgmnt	121	Questionnaire survey	Role of designer
[49]	Tool to design for construction worker safety	Journal of Construction Eng. and Mgmnt	118	Questionnaire survey and interview	DfS tool
[50]	Mitigating construction safety risks using prevention through design	Journal of Safety Research	111	Process-oriented approach	Concept

Table 4
Top authors with at least five DfS publications.

Scholar	Affiliation	Country	Documents	Citations	Total Link Strength
Gambatese, J. A.	School of Civil, Construction Engineering, Oregon State University	US	23	967	11
Behm, M.	College of Engineering and Technology, East Carolina University	US	11	672	17
Manu, P.	Department of Mechanical, Aerospace and Civil Engineering, The University of Manchester	UK	12	79	24
Toole, T. M.	College of Engineering, The University of Toledo	US	8	262	7
Mahamadu, A-M.	Faculty of Environment and Technology, University of the West of England	UK	8	46	22
Tymvios, N.	Department of Civil & Environmental Engineering, Bucknell University	US	6	90	9
Che Ibrahim, C.K. I	School of Civil Engineering, College of Engineering, Universiti Teknologi MARA	Malaysia	6	9	10
Belayutham, S.	School of Civil Engineering, College of Engineering, Universiti Teknologi MARA	Malaysia	6	9	10
Teizer, J.	RAPIDS Construction Safety and Technology Laboratory	Germany	5	891	4
Gibb, A.	School of Architecture, Building and Civil Engineering, Loughborough University	UK	5	119	10
Blismas, N.	School of Property, Construction and Project Management, RMIT University	Australia	5	45	4
Lingard, H.	School of Property, Construction and Project Management, RMIT University	Australia	5	42	4
Poghosyan, A.	Department of Mechanical, Aerospace and Civil Engineering, The University of Manchester	UK	5	36	15

Kingdom, and the second group was led by Che Ibrahim, C.K.I. from Malaysia.

3.5. Most prolific countries in DfS research

A countries network analysis was carried out to investigate the most influential countries and the current collaboration network among countries on DfS research. According to the findings (See Fig. 6), the United States and the United Kingdom were the top-ranked countries (60.8% of the published articles) that contributed to DfS research in the construction domain. The higher number of publications in the United States was most likely due to the continuous efforts and initiative by the US NIOSH through PtD National Initiative in embracing the PtD practice. In the UK, the establishment of PtD legislation (i.e., CDM) since 1994 has influenced the progress of PtD research. Australia is the third most influential country in the DfS research network. The findings also revealed that, of the 29 countries that contributed to the DfS research, only ten (with 10.5% of the published articles) were from developing countries.

Following further examination, the strongest collaboration links were found between developed countries US-UK, US-Australia, US-Germany, Australia-China, UK-Australia, and UK-Spain. In contrast, some countries in the network, notably Italy and Singapore had no collaboration links among other countries of the network.

3.6. Keywords co-occurrence analysis

To construct and map the knowledge domain within the DfS in construction, keyword co-occurrence analysis was conducted. Following the suggestions of [51,19] "Author Keywords" and "Fractional Counting" were adopted in VOSViewer for keyword filtering. Setting the minimum occurrence of keywords at 3, initially, 37 keywords met the threshold. However, these initial filtered keywords

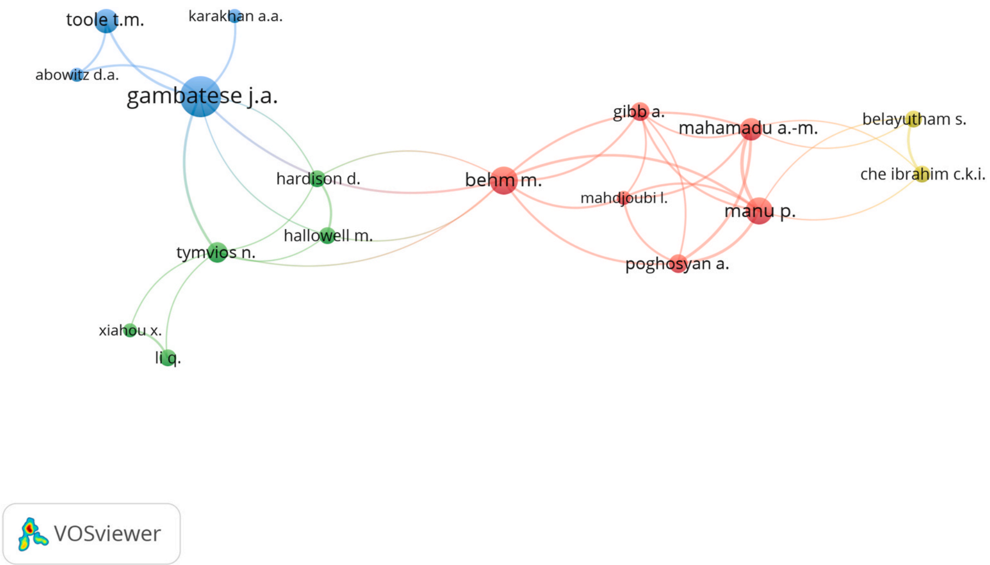

Fig. 5. Science mapping of co-authorship.

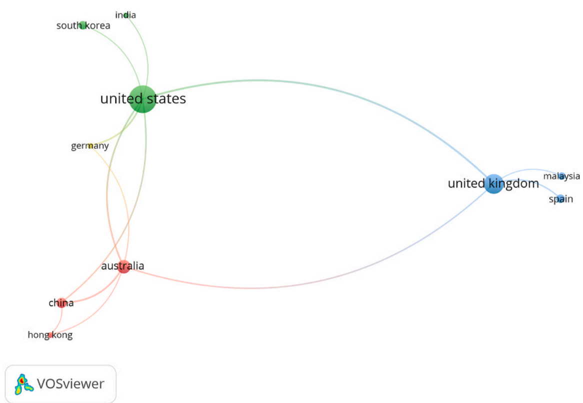

Fig. 6. Collaboration network of countries in the DfS research in construction.

needed further refinement. Keywords such as "prevention through design" and "prevention through design (PtD)"; "BIM" and "Building information modelling" which had the same meaning, were combined into one. General keywords such as "safety", "construction" and "occupational safety" were removed. As a result, a network with 25 nodes and 70 links was created, as shown in Fig. 7, illustrating the context of research identified in DfS research. Examples of keywords details are presented in Table 5.

The analysis revealed six clusters based on the keywords that most frequently co-occur, and these clusters are visualised using different node colours (See Fig. 7). At the center of the network is the keywords "Prevention through Deign" and "Design for Safety" to which all other keywords are connected. Both keywords were mainly published from 2017 till date (see Fig. 8). Cluster 1 contains keywords that promote management. This red cluster includes keywords such as risk management, construction management, project management, owners, accident prevention, and labour and personnel issues. Cluster 2 (green) refers to studies on building information modelling, risk assessment, safety management, hazard recognition, and construction. The rise of these keywords (2017 onwards) could be due to the growing use of technological applications, in particular BIM in safety-related activities. Cluster 3 (in blue) includes keywords (which were mainly published in recent years) related to prevention through design, competence, design professionals, education, and Malaysia. Regulations are associated with Cluster 4 (yellow). Studies related to this cluster were observed in early studies (prior to 2010) due to the introduction of DfS-related initiatives. The keywords are legislative framework, constructability, design safety, and health. Cluster 5 (purple) includes the keywords: safety design, developing countries, and survey. Finally, Cluster 6 is primarily concerned with sustainability.

4. Qualitative discussions

Following the scientometric analysis of the bibliometric characteristics of DfS literature, the in-depth qualitative discussion shifted

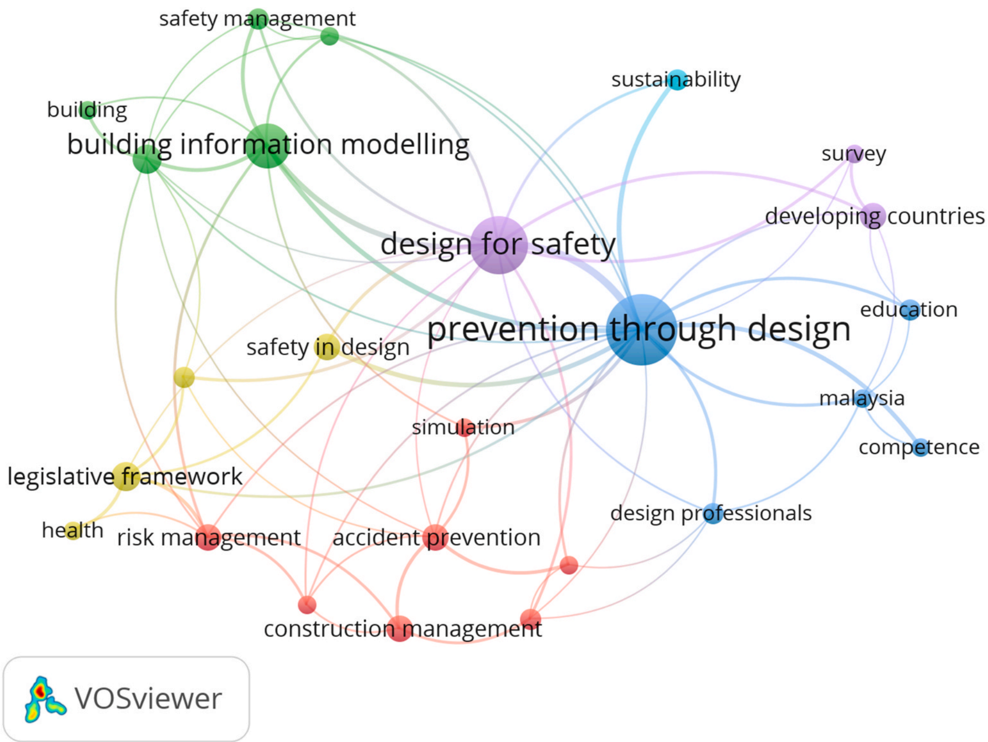

Fig. 7. Network of co-occurring keywords.

Table 5
Examples of keywords extracted from the VOSviewer.

Label	Cluster	Links	Total Link Strength	Occurrences Frequency	Avg. Pub. year
Prevention through design	3	20	30	43	2017
Design for safety	5	15	22	28	2017
Building Information Modelling (BIM)	2	8	13	17	2017
Legislative framework	4	6	6	7	2010
Risk management	1	7	6	6	2013
Developing countries	5	5	4	6	2018
Design professionals	3	5	3	4	2015
Hazard recognition	2	5	3	3	2017
Sustainability	6	2	4	4	2014
education	3	3	2	4	2016
Owners	1	4	3	3	2016
Competence	3	2	3	3	2020

to summarizing emerging DfS topics in construction, identifying existing research gaps, and proposing a framework by linking existing research topics into future directions.

The six clusters of keywords identified from Fig. 8 are interconnected between each of the keywords from different clusters. For example, developing countries and Malaysia both reflect the locality or geographical location. Also, BIM and simulation are both related to the processes in the application of digital technologies. The terms of prevention through design and safety in design are related to the same DfS concept. Drawing on the clustering of keywords, the categorisation of the research themes was established based on an analysis of the context and impact of the keywords on the DfS. For instance, the high frequency of studied keywords, particularly the PtD, DfS was categorised as DfS concept due to its theoretical nature. The keyword of BIM was mainly related to technology, and it is currently being regarded as one of the notable subjects in DfS due to the influence of digital environment on safety. The keywords of design professionals, owners, and competence were categorised as capability and competency. It is worth noting that even though these keywords only represent a small amount of research work (see the frequency of occurrences in Table 5), such studies have a significant impact on the DfS because it focuses on facilitating understanding of DfS professional development as a foundational reference to those countries who have begun or initiated interest in DfS practice. This also applies to keywords related to the educational landscape and sustainability, as both are important elements in ensuring the long-term effectiveness of DfS implementation. Previous studies (e.g. Ref. [52], found that the impact of keywords is sometimes not measurable using the bibliometric data, but rather measured based on its importance for a particular subject. In the light of the foregoing, five mainstream DfS research

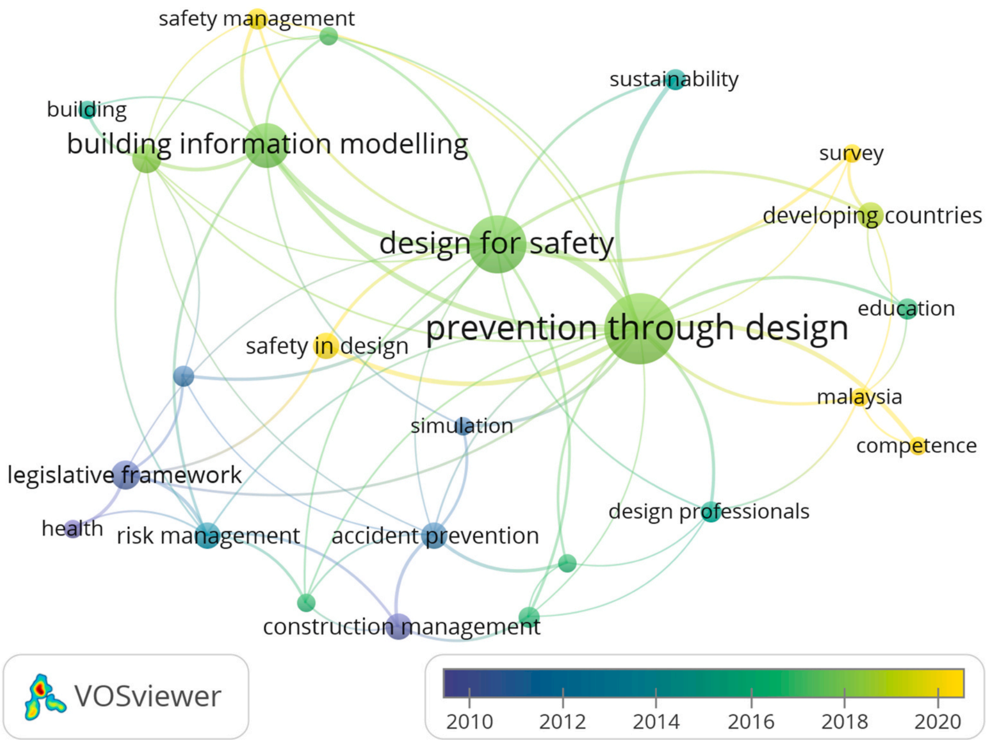

Fig. 8. Overlay visualisation of co-occurring keywords.

themes in construction domain were identified; (1) DfS concept and management; (2) DfS technological advancement; (3) DfS capability and competency; (4) DfS education; and (5) DfS sustainability.

4.1. DfS concept and management

It is evident that two DfS theories i.e., Lorent's 1987 report and [3] Time-Safety Influence Curve, serve as a foundation of the existing DfS knowledge [4]. Based on these theories, prior research has progressively advanced the wider dimensions of DfS concept in the occupational safety and health management of construction projects. Much has been written and acknowledged about DfS as a comprehensive practice of designing out hazards and controlling residual risks of a product, process, or system during the design stage and hence preventing incidents, injuries, illnesses, and fatalities [53,54,55]. Previous studies [5,56] emphasised that each phase of the project lifecycle from concept development to design, construction or manufacturing, operations, maintenance, and even recommissioned/decommissioned should be considered during DfS processes to ensure DfS effectiveness. In addition, research has focused on DfS processes and procedures in various contexts such as conducting hazard and risk recognition using checklists [49]; visualisation tool [57]; and construction modules (drawings, specifications, shop drawings, and miscellaneous schematics) [58]. Scholars have also raised the subject of ownership in DfS management. In particular, the nexus between designers and DfS has come to the attention of several studies (e.g. Refs. [28,59,48,9], and is being recognised as a key influence in DfS because they can proactively design out potential hazards to eliminate or minimize the risk and improve OSH. Building on previous studies (e.g. Refs. [60,53], despite the fact that DfS is expected of designers (architects and design engineers), other stakeholders especially the client (who initiate the project and pays for it) and contractor (the builder of a facility) have been identified as an important duty holders, as DfS practice requires a holistic approach towards coordination and collaboration to ensure the success of fulfilling the roles and responsibilities stipulated in related DfS legislative framework [28]. Having an independent DfS coordinator (from designer or safety professionals) as one of the potential duty holders in coordinating the DfS implementation has also been discussed in the literature [7,14].

Apart from the context of definition, processes, and ownerships, earlier studies have also focused on the viability of DfS as a preventive practice. In particular, the study by Ref. [5] which focused on linking fatalities to project design has provided the empirical justification for most DfS studies into viability of DfS. Further [61,62], provide additional empirical evidence on the potential for DfS practice to reduce construction risks. In addition, studies related to DfS benefits (e.g. Refs. [63,64], and DfS financial implications [65, 11] have also gained interest to further acknowledge and quantify its expected benefits.

Another topic discovered from the analysis is related to the concept is the DfS perception among the key stakeholders and stakeholder role in DfS practice. DfS perception-based studies include the opinion on DfS concept and its implementation in the US [8, 66]; Owner's opinion on DfS barriers [53] and DfS improvement in Korea [67]. On the other hand, most studies on stakeholder roles have focused on designers (e.g., Refs. [48,9]; Vidhyasri and Brahim, 2014 [59]; and owners [68]. The abovementioned studies indicated that while most of the stakeholders were supportive and positive towards DfS, the existence of economic, legal, resource, professional developments, contractual, and procurement obstacles across the stakeholders at project, organization, and industry levels need to be addressed to ensure success of PtD diffusion.

Another important area of research on the DfS concept is DfS legislation. Studies conducted primarily in the United Kingdom (e.g. Refs. [60,69], have focused on how the regulations worked in practice, particularly how the duty holders assumed their roles and responsibilities. Given the distinct nature of construction projects, this effort is significant in providing lessons to construction stakeholders in terms of the practicality of the DfS practice [41]. emphasised that the role of professional bodies in facilitating the regulatory processes, especially in DfS legislation enforcement should be taken into consideration to ensure the statutory implementation is at the optimum level. A multi-faceted approach to enforcement of the DfS practice also has been suggested due to wider dimension of barriers against compliance [54]. Also, the subjects of tools and resources have been highlighted by previous studies as part of the important elements in DfS processes. The application of qualitative and quantitative tools together with wider range of resources (e.g., design, educational) has been emphasised as a mechanism that could inform and educate designers on PtD solutions [49,70].

Multiple current studies also focused on investigating the related factors of DfS implementation. For example, Poghosyan et a (2018) identified five DfS implementation factors (e.g., legislation, clients' influence/motivation, DfS tools, designer awareness/ knowledge and education, and designer attitude). in construction. A recent study by Ref. [71] identified almost similar factors in four categories (i.e., policy environment, practice, guidelines and tools, and education) based on subway engineering project. The findings from these studies provide further support to the growing body of literature on the performance measurement in DfS domain. Despite [12] classified five elements; accidents recorded, risk assessment, workload, health and safety training, perception of safety and health and health and safety management, the importance of having established indicators to measure the degree of DfS implementation in different types of projects remain elusive.

4.2. DfS technological advancement

The focus of technological advancement in OSH has gained interest in recent years mainly in the subject of digital modelling. The work by Hadikusumo and Rowlinson (2002) is one of the early studies that produced a visualisation of the construction process model that can be used to assess safety hazards. The multitude of visualisation-based models (e.g., BIM) is acknowledged to be able to address varying OSH issues, notably in design and planning stage through objective evidence [72,27]. In particular, the function of BIM interoperability could facilitate the safety hazard management through coordination and integration of information and modelling process. For example, the study by Ref. [13] indicated that BIM application could assist the detection and visualisation (through 4D simulation (3D and schedule)) of the potential fall-related hazards during the design and planning phase. Similarly, risk assessment in a 4D environment could be applied as a proactive measure in the design phase to reduce the site hazards [73]. The integration of BIM and safety risk assessment at design stage has also been explored in various dimensions e.g., Safety index [74], DfS knowledge-based library [75]; Yuan et al., 2019), hazard recognition and evaluation [76], risk rating estimation [77] and quantitative risk assessment [78], to define, register and evaluate the risks and hazards between the building elements and hence, facilitate the designers in making informed decisions on the DfS solutions. On the other hand, the use of simulation and visualisation technologies could also be used to mitigate the ergonomic risks, and hence improving productivity [79].

Past studies have also investigated the relationship of BIM with regulatory DfS requirements. For example [80], emphasised that the adoption of BIM level 3 (integration technologies and collaboration) in the UK would offer the duty holders (designer, principal designer, and principal contractor) an alternative mechanism to trigger improved CDM implementation, compliance, and action. Additionally, a study by Ref. [81] in Spain suggested a similar approach (i.e., risk management conducted through BIM common data environments (CDEs)) could enable the integration of OSH in the design phase, aligned with the requirements stipulated by the Spanish health and safety regulations. In a recent study by Ref. [29]; they emphasised that two important directions (i.e., competence development applications and design function applications) need to be considered to ensure the effective DfS implementation through digital technologies.

4.3. DfS capability and competency

The nexus between capability or competence-based measurement and achievement of desired goals (e.g., improving OSH performance) has been highlighted in many construction OSH-related studies (e.g., Refs. [16,82]. In fact, the significance of this topic is well documented in the existing DfS-related legislative framework in various countries [83], where the appointment of a competent designer is required to perform DfS duties. However, the lack of prescriptions in the legislation and literature contributed to a disparity amongst professionals and organisations on the coordination of their capacity to perform the DfS duties (Morrow et al., 2016; [1,84]. To address this issue, past studies initially documented the current state of knowledge, attitude, and practice (KAP) of key construction stakeholders. For example [14,85], investigated the KAP among the civil and structural designers and wider construction stakeholders in Singapore. Similarly [42,40], conducted KAP of Architect in Ghana and Nigeria, respectively. More studies on capturing KAP among designers have also been conducted in different countries, Malaysia [7], Palestine [44], and New Zealand [45]. [86] took a step forward in the DfS KAP literature by comparing the KAP differences between practitioners and academics in Malaysia. It is worth noting that a common finding in these KAP studies is that, while most designers are supportive of DfS, the level of DfS knowledge and practices still needs to be significantly improved. Several approaches have been proposed, ranging from more direct DfS engagement (workshops, training, and guidelines) to more structural approaches that could influence industry dynamics (e.g., collaborative procurements, mandated legislations, etc.).

In recent years, there has been a rise in interest in the topic (i.e., DfS capability and competency), both at the individual and organisational levels. In terms of organisational capability [84], initially identified 18 organisational capability attributes which were subsequently included in the development of a DfS capability maturity model (See Ref. [17]. In a recent study by Ref. [1]; they further indicated that organisational capability is conceptualised as a multi-dimensional construct (i.e., competence, learning, reputation, governance and management system and infrastructure) that can be operationalised at four levels of specificity (i.e., portfolio, programme, project, and task). As for individual competency, the work by Ref. [58] is one of the earlier studies focusing on designer's competence in hazard recognition. They suggested that having construction experience could help designers improve their hazard recognition skills [87]. identified that accessibility to knowledge sources and integration of new and existing project information could facilitate the designer's communication effectiveness towards DfS solution. In another study [16], suggested that designers need to be equipped with tacit and explicit knowledge, technical and soft skills as well as experience related to DfS. They established a conceptual framework of designers' PtD competencies based on 18 key attributes under three domains (i.e., knowledge, skills, and experience). Based on this theoretical foundation [83], conducted an empirical study through a survey and focus group discussion with experienced practitioners to capture the extent of the importance of the attributes towards the PtD practices in Malaysia. On the other hand [28], indicated that the competency of principal designers was framed by the different constructs of knowledge, skills, and experience in five levels of specificity i.e., occupational, organisational, work group, job, and task. Building from previous studies (i.e. [16,83], as the theoretical foundation [88], developed an index as an initial assessment for designers' DfS competence in construction.

4.4. DfS education

Several DfS studies (e.g. Refs. [89,63,90], have indicated the importance of DfS education to tackle one of the most significant barriers (i.e., lack of DfS knowledge) among the construction stakeholders. It is well documented that DfS education is rarely offered and is not a prerequisite for engineering programme accreditation [43,91,92,64]. This concern (particularly in the construction sector) was raised by Mann III (2008), who suggested that broader approaches to DfS education in tertiary education should be explored to maximise DfS application in curricula. Few studies related to DfS education have been conducted in both developed (e.g. Refs. [89,92, 12], and developing countries (e.g., Ref. [43]. For example [12], revealed that, despite an increase in the number of courses dealing with OHS topics, the inclusion of PtD in engineering and architecture courses from Bologna degrees in Spain is low. According to Ref. [92]; the majority of ABET engineering-related programmes in the United States lack Program Criteria or discipline-specific accreditation criteria for safety. In Malaysia [43], discovered a significant gap not only in DfS education but also in OSH education in Malaysian civil engineering programmes.

Regardless of the limitations of DfS education in these countries, common findings indicate that one of the key initiatives to ensure DfS inclusion in curricula is through integration in accreditation bodies requirements [93]. in their studies found that a number of PtD-related topics (e.g., PtD introduction, PtD design phase, PtD professional responsibility, PtD standard, and PtD modern tools and methods) could be introduced to align with the existing US Accreditation Board for Engineering and Technology (ABET) General Criterion 3: Student Outcomes. Similarly, a recent study by Ref. [43] suggested that similar topics could be incorporated in civil engineering programmes to align with the 12 programme outcomes specified in the Malaysian Engineering Program Accreditation standard 2020 under the Engineering Accreditation Council (EAC) (full signatory of the Washington Accord).

Furthermore, some studies have concentrated on the micro-level of DfS education, specifically the pedagogical approach that can be used in DfS teaching and learning [89]. proposed that using case studies as part of a DfS educational intervention exercise could influence students' design thinking in terms of accident causality, prevention, and hierarchy of controls [94]. proposed three techniques (i.e., What if/Checklists, Failure Mode Effects Analysis and Preliminary Hazard Analysis & Risk Assessment) that could be embedded in the curriculum model that aligned with outcomes-based learning to nurture the low to high levels of skill acquisition among the students. On the other hand [90], proposed eight approaches (optional educational activities) ranging from traditional lecture-based to educational modules that cover wider DfS dimensions. In contrast [95], suggested that non-traditional approaches such as computer-based serious game is more effective to instil in the students, safe design thinking compared to a traditional teaching approach.

4.5. DfS sustainability

There have been so far a limited number of studies focusing on how DfS could influence the three pillars of sustainability (i.e., economic viability, environmental protection, and social equity) in construction. Several scholars (e.g. Refs. [11,96,55], have suggested that DfS initiatives are an emerging concept that could leverage the sustainability aspects towards the construction safety and health. Existing studies on green designs [97,98], design options [11,99], and sustainable design and construction [100,101] have suggested PtD strategies are of imperative importance in the effort to achieve the project performance in three key areas: environmental (e.g., reducing pollution and energy consumption), economic (e.g., reducing material/operation costs), and social (e.g., improving the health and comfort of building users). Moreover, although DfS case studies pertaining to green building projects (through LEED rating system) [102] and solar installation [98] can facilitate the holistic approach of sustainability, limitations inherent in DfS practice (e.g., awareness, knowledge, liability, cost) may require the alternative methods or approaches to advance the sustainability [101].

5. Future research directions

Based on the summarized status quo of research information on DfS in construction (See Fig. 9), several corresponding future research directions can be further explored by analysing what remains to be done and where attention should be directed, specifically;

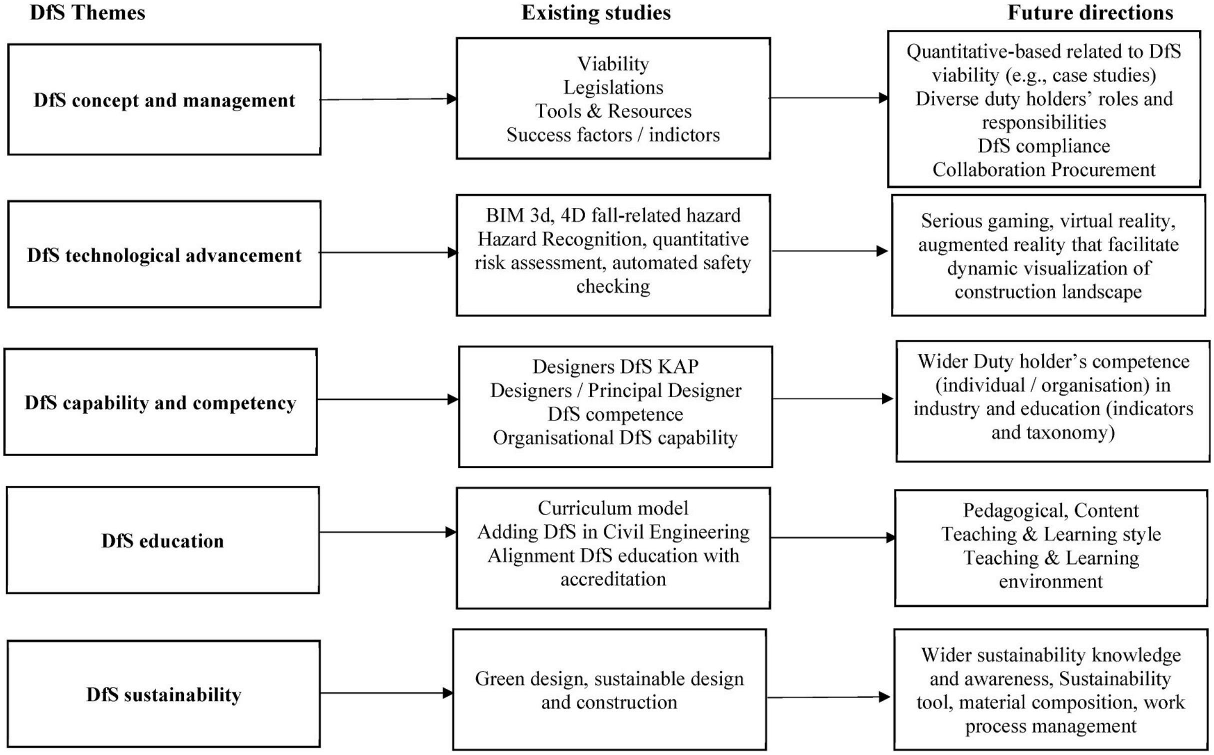

Fig. 9. Framework of status quo of DfS research and its future directions.

- Prior research has progressively advanced on the concept, processes, motivation, and viability of DfS mainly through a qualitative approach [27]. More quantitative-based studies must be conducted continuously to support the theory objectively and hence facilitate the DfS business cases. Upon further observations, more attention on the contractual modifications, determining ways to expand recognition and rewards for facilitating DfS should be considered in order to increase the DfS viability and hence provide a positive return of investment of DfS implementation. Additional limitations that have been identified especially on the subject of DfS ownership should also be addressed in future research. Given the unique nature of stakeholder's involvement (depending on the procurement method) in most construction projects, more case studies of real DfS projects focusing on different types of duty holders such as principal designers, principal contractors, design coordinators, and regulators are needed to capture the wider landscape of DfS roles and responsibilities and hence, providing the lived experiences of practicing DfS. Also, the focus could be extended to designers of facilities that are responsible for the specifications of design and construction tools and materials as they could influence DfS solutions on tools, equipment, materials, and work processes. The impact of having collaborative procurement approaches (e.g., integrated project delivery, alliance, and early contractor involvement) on DfS practice should also be investigated through longitudinal research in order to provide a better understanding of the DfS management.
- The integration of DfS and technologies has been attracting significant interest in recent years. Studies have indicated that technological advancement in construction (e.g., BIM, VR, AR) offers a collaborative platform for the OSH in construction to be managed in a digital environment. From the analysis, more applied research is suggested on enriching the integration between DfS and BIM as well as other technologies (e.g., serious gaming, virtual reality, augmented reality) in terms of connecting the knowledge-based system with extended design (architectural, structural, mechanical and electrical) elements, automatic rule checking system, clashes detection, dynamic visualisation that could mitigate risks and hazards with proper design consideration. Such studies are critical as part of efforts to build a comprehensive overview of digital applications on DfS and could provoke further debate on the need to consider technology in OSH management. Also, it is worth highlighting that the current COVID-19 pandemic could also offer an opportunity for future research in terms of mitigating the biological hazards, for example, the accessibility and logistics management in the construction site that could be considered early in design phase. The investigation of relationships between the DfS guidelines or code of practice and extended BIM requirements in different geographical locations could also provide more insight into the role of duty holders in the discharge of DfS obligations related to information production, provision, and exchange in a digital environment. Moreover, the fact that BIM platform allows the high-level collaboration between multi actors to exist, quantifying the information shared and data exchanged (design or OSH-related) among the actors into a common platform could be further investigated. Such future studies could provide a greater understanding of the feasibility of technology and DfS interoperability.
- The subject of competency and capability has been acknowledged as an emerging research direction as it contributes to minimizing the industry and academic gap on DfS competence by providing the necessary foundation for duty holders (particularly designers)

and design organisations to improve their DfS endeavours and hence, facilitating them to fulfill their responsibility under relevant OSH legislative framework. Nonetheless, more studies on strengthening this theoretical background (e.g., validating or testing the identified attributes/constructs) are required to further assess its practicality (e.g., as prequalification assessment in procurement, relationships between constructs, its impact towards construction processes) and enhance the potential development of competence or capability measurement model. Future studies focusing on different competence profiles of duty holders such as principal contractors, regulatory bodies, and clients as well as different sizes of organisations (e.g., SMEs) can also be considered [54]. highlighted that there is considerable room for improvement in the area competence assessment of DfS duty holders as such assessment could provide better understanding for the duty holder in discharging their role. Also, the competence profile of academic/educational institutions and educators could also be explored to ensure the success of DfS diffusion in the educational landscape. Establishment of taxonomy descriptions of the attributes/constructs across different duty holders and investigating the enablers and challenges of individual competence or organisational capability in different levels of specificity (e.g., job, task, work group, etc) are another interesting direction that remains as an open and challenging task.
- While the application of DfS has been increasing in both developed and developing countries [90]: [43], the research works related to DfS education are still evolving. To facilitate the DfS in the educational landscape, researchers may focus on further improving the sense of presence by investigating the barriers that prevent DfS from being included in curricula (e.g., crowded and strict curriculum, balancing different institutional requirements, interdisciplinary knowledge) as well as teaching and learning opportunity topics (e.g., ethics, policy, sustainability, technology, project lifecycle). Also, more research is required to advance the current state of DfS education in various countries by capturing the status quo (e.g., current implementation and view of academics) to see the similarities and differences and hence providing a guidance on the potential of how DfS education could be integrated (either through safety adoption, safety integrator or safety adaptation) with their respective accreditation bodies. Another challenge is to explore new innovative pedagogical and constructivist learning approaches (e.g., assessment, course alignment), learning styles and environments, and educational resources that could add value to the DfS education exercise.
- Establishing the links between DfS and sustainability is considered to be an ongoing interest that needs to be further explored. As illustrated in Fig. 8, the emphasis of current research on the subject sustainability is relatively insufficient. Future efforts can be made to further explore the impact and challenges of DfS in the operationalisation of sustainability in different dimensions (economic, social, and environment). In view of this, more empirical studies on DfS application (through case studies) related to sustainability has been recommended. Also, the scope in terms of the knowledge and attitude of key stakeholders, safety and health legislative framework, and sustainable practices or technologies (e.g., green design elements, low energy, low-emitting materials, modular construction) could also be considered to provide more detail insight on the DfS benefits towards the worker health and safety, and hence facilitating the owners and designers in making informed decisions for DfS practice.

6. Conclusions

This scientometric review study aims to provide an overview of the current trends of DfS practice in construction based on the available literature. A total of 167 articles, published between 1974 and early 2022, were identified and reviewed. It was found that DfS has received much attention from scholars, especially since 2007. Prolific journals in the domain of DfS research were identified to be *Safety Science*, *Journal of Construction Engineering and Management* and *Automation in Construction* are the key journal publishing on DfS in construction research. The United States, United Kingdom, and Australia are the countries that dominate the publication while developing countries were underrepresented in the network despite countries such as 'Malaysia' are growing in DfS research due to the recent introduction of DfS guidelines in 2017. Based on the analysis, the most prominent research topics are those relating to the use of BIM in DfS practice. DfS and PtD usage were also identified as the most co-occurring keywords.

Following the scientometric analysis, the qualitative analysis summarized five main research DfS themes, which linked existing research topics to future research directions including but not limited to; 1) more DfS studies related to concept and management (e.g., viability, legislations, procurement, processes) that adopted quantitative-based methodologies; 2) wider application of technological advancement for DfS practice; 3) explicit and practical capability and competency measurement for DfS duty holders; 4) continuous DfS pedagogical studies to address the gap in DfS educational landscape; and 5) wider application of DfS towards sustainability. In principle, more studies that use various methodological frameworks and linked to the real working environment, as well as cross-country comparative studies are needed to expand the current research progress of DfS towards strengthening and validating the theories and practice in diverse settings.

A possible limitation of this study is that this review study is not extensive (e.g., limited to articles in English-based academic research) and only limited to the construction domain. Nonetheless, the information presented in this article provides an insight into the research progress made in the domain of DfS research, and it can assist researchers and practitioners in identifying fundamental influences from authors, journals, countries, institutions, references, and research topics. The analysis of these contributions to DfS research may also facilitate scholars and professionals in seeking further collaborative research opportunities, thereby bridging the gap in understanding the practical concerns of DfS practice in the construction industry.

Declaration of competing interest

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

None.

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