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Global Research Productions Pertaining to Design for Safety: A Bibliometric Analysis Based on WoS Database

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Abstract: Design for Safety (DFS) is a crucial tool that assists humans in paying closer attention to safety and health in project life cycles of buildings and other facilities. Analyzing DFS through a bibliometric perspective can facilitate the development of new theories, promote disciplinary content, and reveal the direction of development in the subject area. This paper presents a systematic, holistic, and comprehensive overview of the global literature focused on DFS, summarizing the number of publications, research hotspots, research methods, and distribution. Scientific publications are a measure of academic level and scientific strength of institutions and individuals, and this article provides an overview of interdisciplinary research on DFS from 1 January 1997 to 31 December 2020, based on literature related to DFS in the Web of Science database (WoS-database). The paper highlights current research hotspots, ideas, and trends around the world, offering a global overview of contemporary and interdisciplinary research in DFS. By utilizing both keyword clustering and co-citation clustering techniques, the paper proposes the 4P framework (i.e., purpose, people, procedures, and phenomena) to better understand current global achievements and to achieve a complex structure for future development. This concise description of DFS trends may provide a logical mechanism for assessing and understanding the development of DFS research.

Keywords: design for safety; prevention through design; bibliometric analysis; project life cycle; hazards; injuries

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1. Introduction

Construction and maintenance works of buildings and other facilities involving temporary or transient working environments pose inherent risks and hazards. Managing safety throughout the project life cycle is a key factor in ensuring the personal safety of employees, promoting the smooth construction of projects, and creating a safe social environment [1–5]. The design for safety (DFS) concept focuses on personnel safety issues during construction and maintenance, with the aim of reducing potential risks to personnel during these stages by taking measures during the design stage, and ensuring personnel safety and health in the work environment [6–8]. It is related to all aspects of the country and individuals and provides an important part of building a harmonious society by reducing safety accidents and ensuring personal safety [9–11]. Evidence has shown that DFS is closely associated with eliminating or reducing construction safety risks in advance and implementing the safety responsibilities of designers, laying the foundation for life-cycle safety management of construction projects [12–14]. Ironically, despite the recognition that safety design has as a large function to decrease the frequency of construction accidents and safeguard the lives of workers, managers in actual construction projects still do not adequately use safety facilities or may violate regulations, resulting in serious consequences [15,16]. For example, personnel in charge of construction sites do not purchase and issue safety equipment (e.g.,

helmets) to workers as required, while often a piece of safety equipment can guarantee the safety of workers' lives. To ensure the safety of workers during construction and maintenance works, as well as end users, it is essential to carefully consider both temporary and permanent design solutions. Designs that do not take safety into account may even result in the killing of workers [17–19]. Achieving personnel safety, construction process safety, and maintenance stage safety requires comprehensive consideration and careful design [20–25]. Designing with safety in mind is essential for human health and the betterment of society [26]. According to statistical data, from 1994 to 2004, the number of fatalities associated with construction safety accidents in mainland China reached 15,128, with an average of 1375 deaths per year. This reveals the fragments and flaws of safety management in the construction industry. When an incident happens, it is bound to result in various significant losses such as property and life, etc. [27–29]. Determining how to avoid hazards in the project life cycle, to reduce the economic loss and injuries caused by construction and maintenance disasters is a subject that needs to be studied urgently [30–33].

According to the view that DFS is the basic guarantee of project life cycle safety, designers are beginning to pay attention to safety issues of construction workers. The latest research in the field shows that considering safety issues in the design phase can effectively eliminate or reduce project life-cycle safety risks. Designing for safety has also gained considerable attention as an early intervention in safety management, and relevant laws have been introduced in many countries to hold designers accountable for safety issues. Institutions and organizations worldwide are actively contributing to research on DFS, and there is a growing need for a comprehensive and systematic review of this field [34–36]. Institutions and organizations around the world are concerned about DFS and offer different kinds of scholarly publications relevant to this subject [37,38]. Bibliometric methods are an effective way to analyze and summarize large numbers of publications and to identify research hotspots and trends [39,40]. By using bibliometrics, we can gain a macro view of the technical contours of DFS, which is especially useful in cases where the existing literature is fragmented across different disciplines. While a literature review can offer a more detailed analysis of the content of individual papers, bibliometrics can provide a broader and more comprehensive overview of the field.

To date, there has been a lack of a large and detailed overview of scholarly studies on DFS. Therefore, this article employs a vertical bibliometrics review to provide a global analysis. By analyzing the literature related to DFS, the article presents current research hotspots and value ideas, and summarizes global trends, providing an interdisciplinary perspective on contemporary research in this field [41,42].

Using keyword aggregation and self-selection aggregation, the article proposes a 4P framework to promote a greater appreciation of current accomplishments in DFS and to create a complex structure for future development. Overall, this article demonstrates the importance of DFS and emphasizes the need for ongoing investigation in this field to advance safety outcomes.

2. Methods

2.1. Overview

This paper uses bibliometrics to analyze research in the field of regression DFS. Bibliometrics uses the literature as a foundation and present an objective study of the current condition of the discipline and trends in the development of the discipline through a multi-faceted statistical analysis of the number of papers, publications, journal sources and subject distribution in a particular subject area. With the help of bibliometrics in a particular field, it facilitates the germination of new theories in the field, promotes the development of disciplinary content and provides direction for the development of the disciplinary field. The bibliometric analysis entailed a massive evaluation of over 70.8 million papers on the Thomson Reuters Web of Science Core Collection. It was designed to provide a current and holistic overview of the literature on DFS for the period 1997 to 2020 and to determine important chances for an upcoming study. This approach allows for an objective evaluation

of the development status and level of each category of literature, as well as predictions of current trends and tendencies in science and industry based on the quantity and quality of literature output [43–46].

At present, bibliometric analysis is acknowledged to be one of the strongest active branch subjects in the field of international libraries and information has emerged as the dominant scientific study of information and reflects the tendency of the discipline of contemporary subjects [46,47]. Bibliometrics is a quantitative and practical discipline. It serves an essential function in studying the distribution law and quantitative relationship of documents, as well as the internal relationship between documents, and revealing some laws, characteristics, and structures of science and technology. When compared with the conventional critical review approaches, bibliometrics has distinct strengths in revealing the embodiment structure and data changes in the law of the discipline field, and improving the science and accuracy of mining information. To visualize the citation impact of the literature, we used the h-index variable, which represents the number of papers that have been cited at least h times each. By applying this approach, we can measure the significance of the literature and identify influential authors and works.

In conclusion, this paper demonstrates the usefulness of bibliometric analysis for studying the development and trends of research in DFS. Through a statistical analysis of literature, we can gain valuable insights into the field, promote disciplinary content development, and guide future research.

That is why more granular and targeted outcomes could be acquired via traditional methods. In the present research, the three stages of data collection, data analysis and research focus are followed for bibliometric analysis. Firstly, in the data collection section, we carry out two steps: search term selection and data screening; secondly, in the data analysis section, we divided the data into social network analysis, co-citation analysis, keyword cluster analysis, and burst detection; finally, the research focus is divided into two parts: the intrinsic connection of research subjects and the core theme evolution.

2.2. Data Collection

We mainly study bibliometrics in the field of project management. Seeking relevant publications that avoid drawing narrow search boundaries presents a particular challenge. Two practical strategies have been applied to determine the related research. First, specialist interviews were conducted to enhance the search for these keywords. The keywords identified included: safety design, design prevention, design, prevention, inspection, decision-making, risk assessment, model, knowledge, prevention through design, and management. Second, the Web of Science Core Collection was chosen as the primary database which comprehensively includes mainstream leading scholarly journals for a significant period as well as provided detailed dates, particularly the references of publications. Non-compliant papers were removed and only those in journals and languages of English were selected. A total of 210 compliant papers were screened and selected as the sample set for the period 1 January 1997 to 31 December 2020 (the time of data collection).

2.3. Analysis Approaches

This study adopted four bibliometric methods: social network analysis, co-citation and co-occurrence clustering, as well as burst detection, which were utilized to investigate the structure and evolution of DFS.

2.3.1. Social Network Analysis

Based on mathematical methods and graph theory, the social network analysis method is conducive to the visualization of network structure. Through the calculation of specific parameters (e.g., degree, betweenness, and closeness centrality), it helps determine the relationship between characteristics of publications (e.g., correlations including authors, research institutions, journals, and countries), strengthen the research of embedded information and highlight the entire scholarly field. In this paper, the social network analysis is

carried out by first identifying search items, fields and statistical time: in the web of science core collection database, the title, subject, keywords and abstract are searched, and then the literature is filtered: the literature is filtered by whether it is relevant to the research topic and whether the journal source meets the search criteria.

2.3.2. Co-Citation Analysis

Co-citation analysis explores the relationship between the individual study and the surrounding literature. The object of study is the literature, and multivariate statistical methods such as cluster analysis and multidimensional scale analysis are used to simplify the intricate co-citation network relationships between the many objects of analysis into relationships between a number of taxa with relatively little data, and to visualize them. The basic principle of co-citation analysis is to take a batch of literature with a certain discipline representation as the analysis object. It is the co-citation analysis on a batch of literature (or authors, journals, and institutions), utilizing agglomeration profiling, multidimensional zooming, and other multivariate statistical analysis methods. The analysis steps are as follows: the citation matrix is obtained by induction from the literature information, and the co-citation matrix is generated on the basis of the citation evidence. Using visualization techniques, the co-citation matrix is visualized as a network. Through the support of computers, the multiple complex co-citation network relationships between numerous analysis targets are reduced to the relationship between a comparatively low number of sets and intuitively represented. The two publications are quoted in other papers in the meantime and the number of documents quoting them is taken as the co-citation intensity. The greater the co-citation strength, the higher the degree of similarity between the publications, and the smaller the degree of similarity between the two.

2.3.3. Co-Occurrence Analysis

Co-occurrence analysis is a common research approach in bibliometrics, which quantifies the co-occurrence information in various information carriers. According to the terminology of network analysis, the co-occurrence of keywords (or topics, authors, and institutions) forms links in the network. It reveals the internal correlation between academic research content in a certain field and the micro-structure of the subject field [48,49]. In the resulting clustering, the keywords with a high frequency clearly outline the core theme and content of a particular research field. Co-occurrence analysis also helps to elucidate the fabric of knowledge, relational networks, and evolutionary processes in a given field, and to shed light on key subjects of investigation in the primary literature. Before performing a supply word analysis, one first needs to comprehend word frequency analysis. Word frequency analysis involves counting the occurrences of each word in the document being analyzed. Word frequency analysis is a method of extracting the frequency plateau distribution of keywords and subject words that express the core content of a document to study trends and research hotspots in the field. A higher level analysis of the word frequency network, based on word frequency analysis, is called co-keyword analysis. The basic principle of co-keyword analysis is to count the number of times a group of two words appear in the same set of literature, and to measure the affinity between them by the number of such co-occurrences.

2.3.4. Burst Detection

Burst detection is a technique used to automatically discover and detect bursts in sequence and is a common sequence analysis technique where burst detection can be designed to parse changes in a group of keywords or publications to identify pointing transitions. The burst detection module is used to detect sudden increases or decreases in the number of keywords or citations in a short period of time by detecting prominent points of change in the number of keywords or citations. In this paper the procedure is to select the frequency of the word or phrase used to detect the decline or rise of particular topic word or keyword.

Before performing a supply word analysis, one first needs to understand word frequency analysis. The frequency of a word in a document is referred to as its word frequency. Word frequency analysis is a technique used to extracting the frequency plateau distribution of keywords and subject words that express the central theme of a document to study trends and research hotspots in the field. A higher-level analysis of the word frequency network, based on word frequency analysis, is called co-keyword analysis. Co-keyword analysis is based on the frequency of occurrence of pairs of words in the same set of literature. By measuring the number of co-occurrences of these pairs, the relationship or affinity between the words can be determined.

Overall, the study employs a range of bibliometric methods to analyze safety design in project management, which offers insights into the evolution and structure of this field.

3. Results

Subheadings can be used to organize this section, which should contain a clear and succinct explanation of the experimental results, their interpretation, and the conclusions that can be drawn from them.

3.1. Research Trend

3.1.1. Overall Trend

As shown in Figure 1, since 1997, the publication of DFS has grown steadily year by year, indicating a growing academic interest in the field. From 1997 to the present, the total quantity of publications fluctuated up and down, and there was no considerable rise in the total quantity of publications until 2017. Although the total quantity of publications fluctuated over the years, it did not witness significant growth until 2017. This suggests that research on safety design has been on the rise over the past two decades, indicating widespread interest in DFS. Moreover, this interest has further intensified over the last five years.

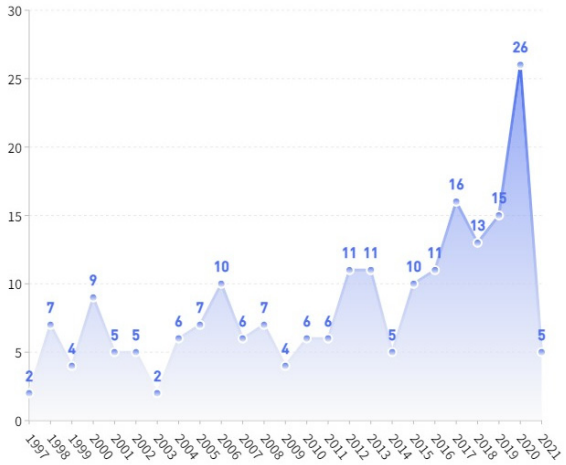


Figure 1. The annual number of DFS publications.

3.1.2. Country Distribution

Figure 2 depicts the geographic locations of organizations that contribute to DFS, and Table 1 lists the H-index of the ten countries with the largest number of publications and productivity. The intensity of the yellow part of the picture is scaled to the volume of publications, that is to say, the more intense the color, the more articles. It is mainly from Table 1 that the region with the deepest yellow point is America.

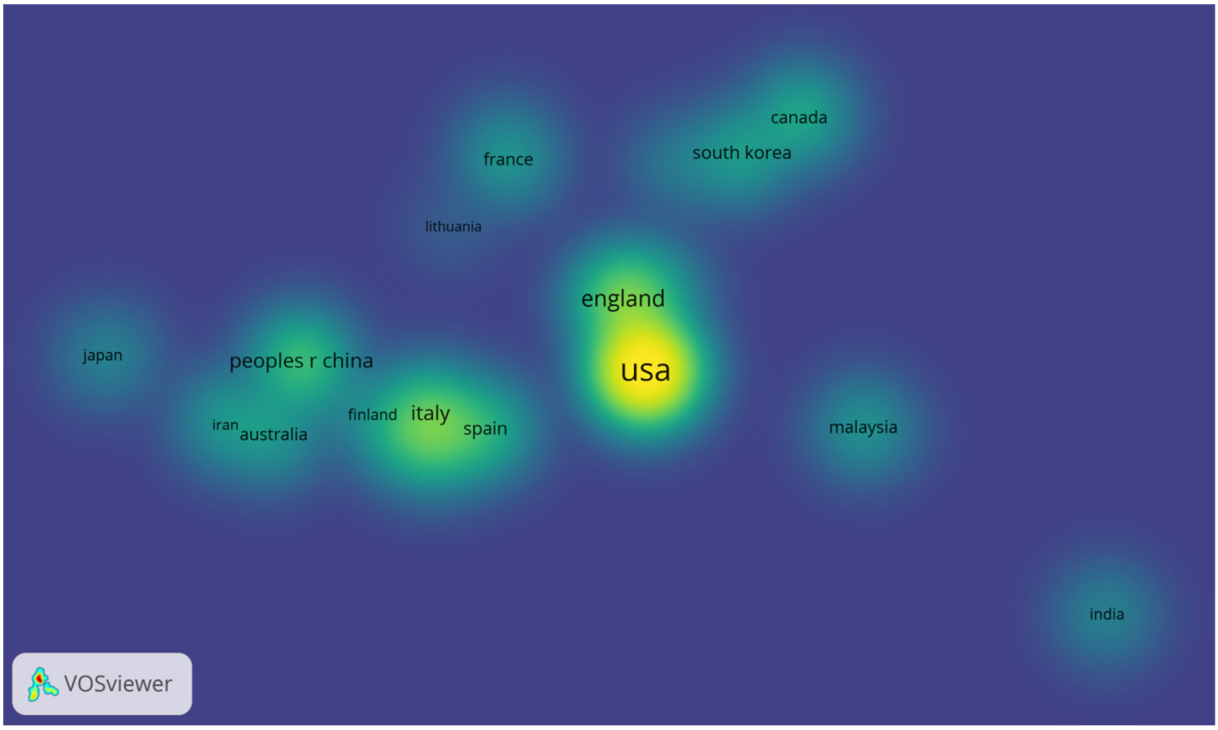


Figure 2. Geographical distributions of DFS publications.

Table 1. The top ten most productive countries regarding DFS.

Rank	Country	Frequency	Centrality	H-Index
1	USA	67	0.34	15
2	UK	27	0.09	8
3	China	25	0.18	9
4	Italy	13	0.05	5
5	Germany	11	0.04	3
6	South Korea	10	0.00	4
7	Netherlands	9	0.04	5
8	France	8	0.05	3
9	Singapore	7	0.05	6
10	Canada	6	0.00	1

A grand minimum of 54 countries or territories engaged in the DFS research, including established and emerging countries. A total of 54 countries or territories are involved in DFS research, comprising both established and emerging countries. The top ten countries in terms of the publications are primarily located in the Americas, Europe, and Asia, indicating that these countries have a greater interest in construction safety than others. England was the first country to initiate research on DFS in 1997, and it has the second-highest citation frequency worldwide. The United States holds the highest citation frequency at 67, establishing its dominant position in this field. This can also be observed in the H-index.

It is worth noting that among the top ten participating countries in DFS research, nine of them are developed countries, accounting for a significant proportion. The reason for this distribution seems evident: these countries attach great importance to the initial stage of the project life cycle and focus on improving the design quality to minimize safety hazards and reduce construction risks.

China has performed exceptionally well in this field, occupying the third position worldwide. With the rapid expansion of China's architecture sector in recent years, safety issues caused by unsatisfactory building performance have inevitably arisen. Under these circumstances, the intervention and control of building quality in the design stage

have become particularly important, attracting significant attention from the academic community.

In conclusion, the interest in DFS has been growing steadily over the past two decades, and the attention towards it has further intensified over the last five years. The top ten participating countries in DFS research are primarily located in America, Europe, and Asia, indicating that these countries attach significant importance to construction safety. China's performance in this field is particularly noteworthy, given its developing country status and the significant attention it has devoted to building quality control during the design phase.

3.1.3. Institutional Analysis

Table 2 presents the top ten most prolific institutions that have contributed to research on safety design, along with their corresponding frequencies. Notably, Oregon State University is the institution with the highest frequency, followed by other US-based institutions such as Bucknell University and East Carolina University. It is worth noting that these three universities all began their research on safety design in 2005.

Table 2. The top ten most productive institutions regarding DFS.

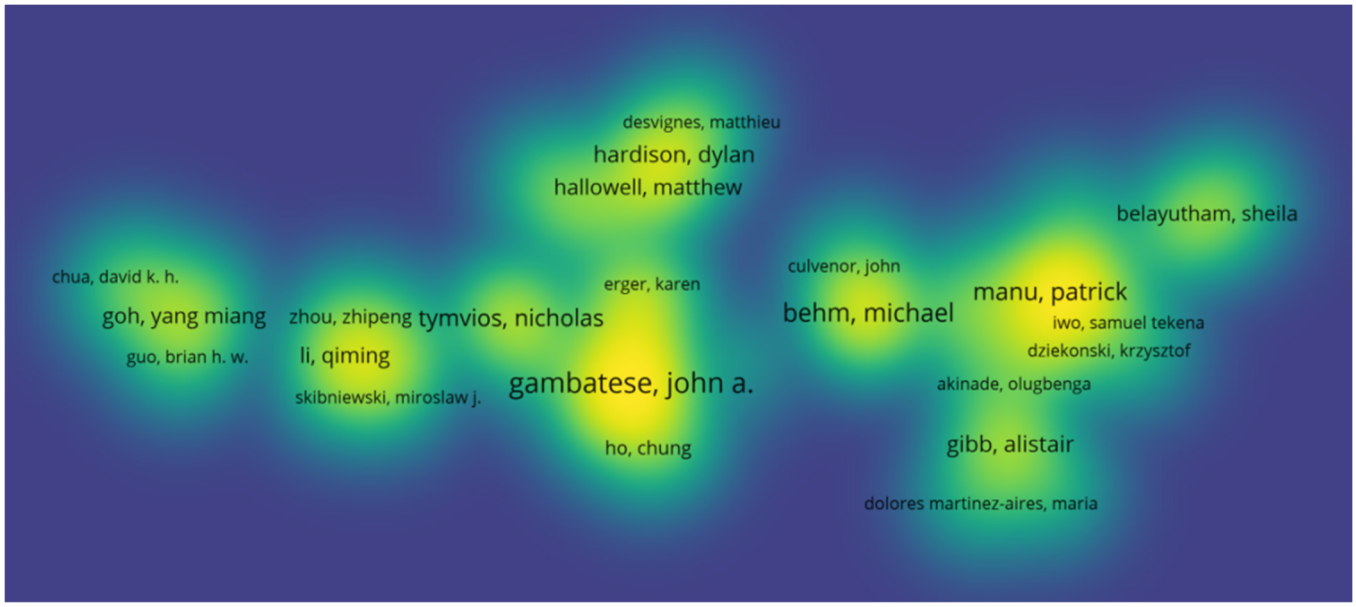
Rank	Institution	Type	Start Time	Frequency
1	University of North Carolina	University	2005	10
2	East Carolina UNIVERSITY	University	2008	9
3	National University of Singapore	University	2010	7
4	Oregon State University	University	2008	6
5	Sapienza University Rome	University	2017	6
6	Liverpool John Moores University	University	2016	5
7	South East University	University	2005	5
8	University of Colorado Boulder	University	2008	5
9	University of the West of England	University	2019	5
10	University of Strathclyde	University	2005	5

In addition, the only research institute in the top ten is the National Institute for Occupational Safety and Health (NIOSH), which was established by the US Ministry of Health, Education, and Welfare to develop new occupational safety and health standards and train professionals.

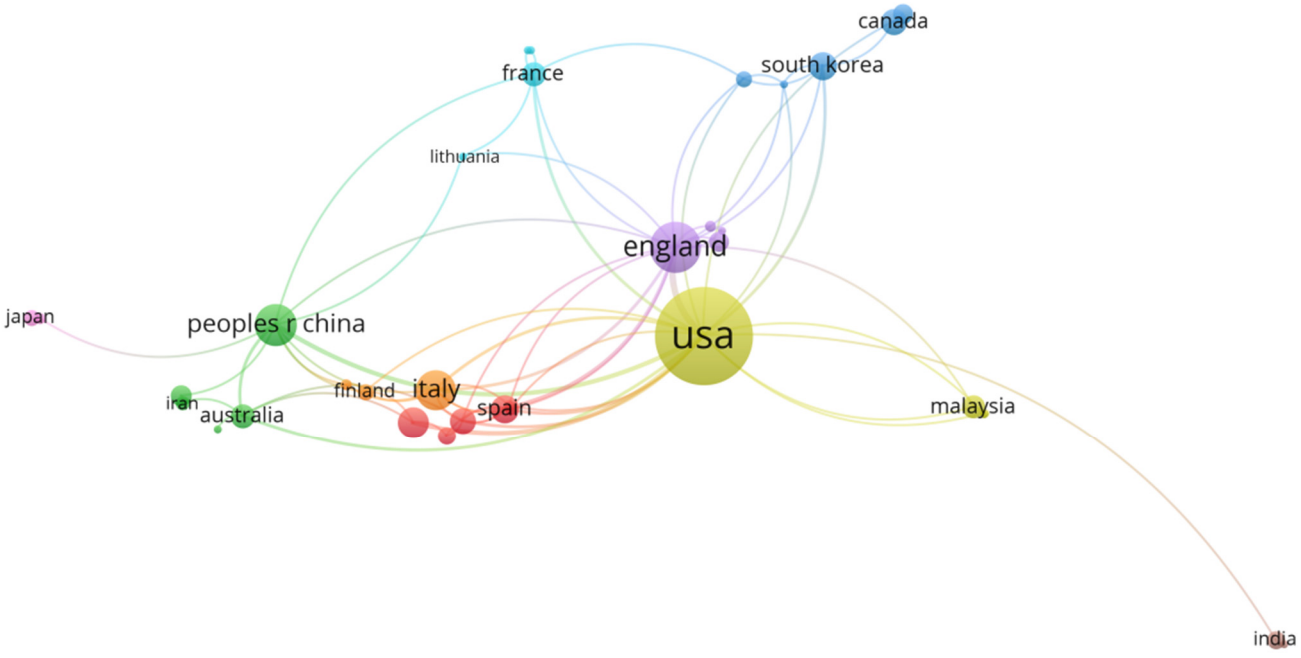
3.1.4. Author Analysis

Figure 3a maps the geographical position of the enabling organizations that contribute DFS and the authors who produced the most content for DFS are presented in Table 3 including when their research started. The depth of the color in the graph is directly proportional to the number of authors, which implies that the more intensified the color, the more articles there are. The intensity of the color in the graph represents the number of authors, with a higher intensity indicating a higher number of articles. The Americas have the highest density of yellow dots, indicating that this region has contributed significantly to research on safety design. This finding is further supported by Figure 3b, which shows

the clustering of publication countries. The link between economic development and the importance attached to safety is evident in the high level of research activity in the Americas.



(**a**)



(**b**)

Figure 3. (**a**) Geographical distributions of DFS Authors. (**b**) Co-occurrence of DFS countries 3.1.5 Journal analysis.

Table 3. The top ten most productive authors regarding DFS.

Rank	Author	Start Time	Frequency
1	Michael Behm	2008	7
2	Mario Fargnoli	2010	5
3	Y.M. Goh	1995	5
4	Qiming Li	2018	5
5	Dracos Vassalos	2010	5
6	J. Wang	2016	5
7	Matthew R. Hallowell	2014	4
8	D. Hardison	2019	4
9	Patrick Manu	1995	4
10	Steve Rowlinson	2016	4

Table 3 shows that writers began to study safety design in the 1990s, and since the twenty-first century, with the development of the economy, increasingly writers have conducted research on safety design. The first authors to publish articles in this field were Y.M. Goh and P. Manu, with a publication time of 1995. M. Behm, an author of the highest aggregate number of articles, discusses the critical role of safety design in preventing fatalities in construction. Meanwhile, only a small number of authors have published more than three articles, indicating that most authors are still in the early stages of their research on DFS.

3.1.5. Journal Analysis

Scholars from various countries contributed to articles published in 306 different international journals covering topics such as safety, management, construction, and ergonomics. Impact factor (IF), is a quantitative indicator of the impact of a journal. The IF of a journal is a measure of the standard of the journal. Other variables are also explained in the text. As shown in Table 4, Safety Science published the most articles, while Automation In Construction owns the highest impact factor. A combined 88 articles were published in the top ten journals, which accounted for 83.01% of the total.

Table 4. The top ten most productive journals regarding DFS.

Rank	Journal	Records	IF
1	Safety Science	17	4.877
2	Automation in Construction	5	7.7
3	Journal of Construction Engineering and Management	5	3.951
4	International Journal for Quality in Health Care	4	2.038
5	Lecture Notes in Computer Science	4	1.093
6	Applied Sciences-Basel	3	2.679
7	Journal of Engineering Design	3	2.588
8	Marine Technology and SNAME News	3	0.125
9	IEE Proceedings—Science, Measurement and Technology	2	1.0993
10	Engineering, Construction and Architectural Management	2	3.531

3.2. Co-Citation: Journals and Authors

3.2.1. Journals

Figure 4 presents a dual-map overlay of journals, with the left graph showing the cited journals and the right graph showing the citing journals. Figure 4 shows the dual-map overlay, a technique used to compare the differences between two maps, usually for comparing map data at different points in time or different geographical locations. In this paper, we use dual-map overlay to compare DFS-related papers published in different regions from 1997 to 2020. Figure 4 shows the distribution of the number of DFS-related papers in different regions of the world from 1997 to 2020, with different colors indicating the differences between the two time points. From the figure, it can be seen that the number of DFS papers published around the world has increased over time. This is consistent with the statistics in Figure 1. Meanwhile, we still use other data analysis methods to further explore the reasons for these differences, including the level of regional economic development, university distribution, etc. The majority of the publications were published in the area of "Mathematics, Systems, and Mathematical" as shown on the left in Figure 5, and these were primarily driven by the areas of "Systems, computing, computer and Psychology" as shown on the right. Journal topics were marked, with citation routes visualized as colored profiles, showing that there were five major citation routes in the current map.

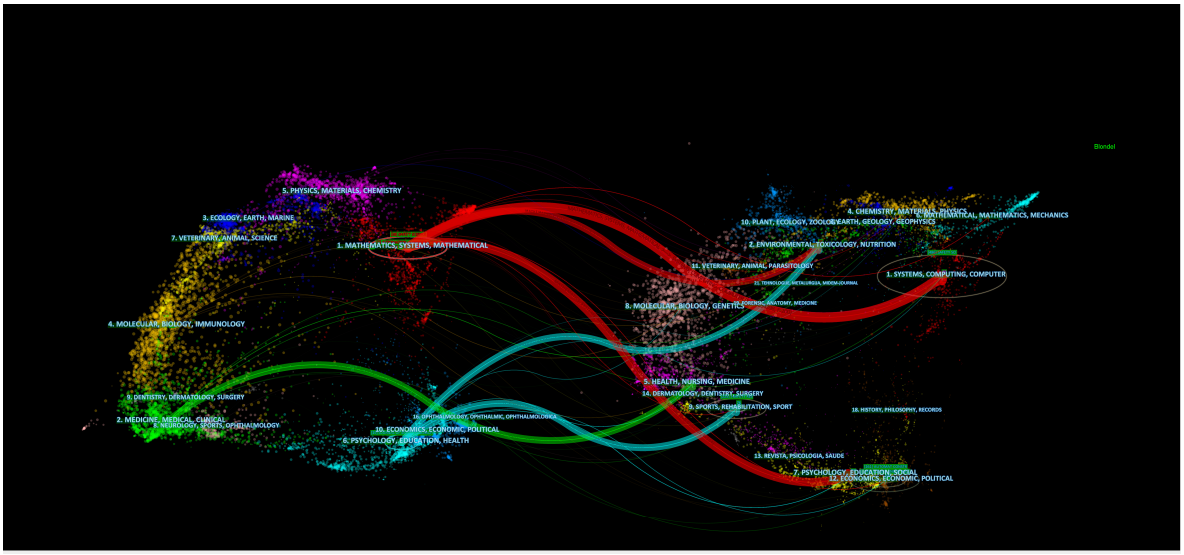


Figure 4. Dual-map overlay of journals related to DFSMap.

3.2.2. Authors

A total of 589 authors were quoted in 210 articles based on VOSviewer (Figure 5). Co-cited authors indicate that the two authors appear in the same paper at the same time, indicating that the two authors have a cooperative relationship. The higher the frequency of co-occurrence, the higher the intensity of cooperation between the two authors, and the greater the degree of correlation.

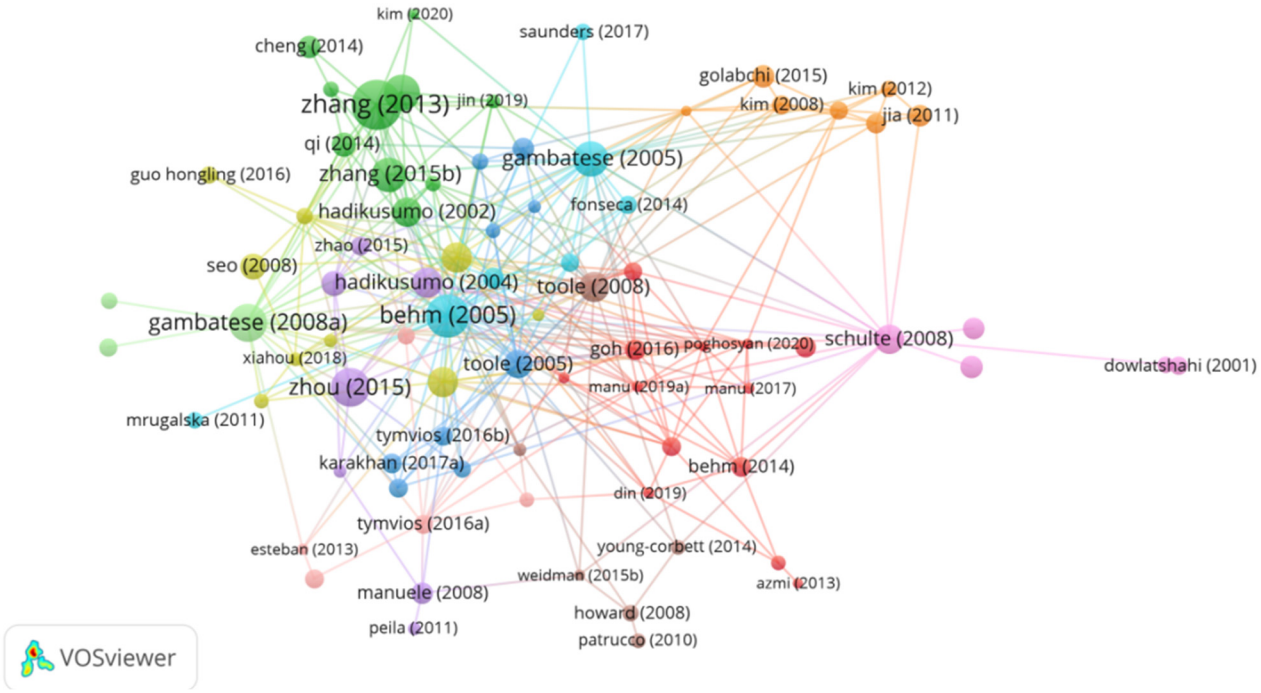


Figure 5. Co-citations for cited authors.

3.3. Highly Cited Publications Analysis

3.3.1. Highly Cited Publications Analysis

Table 5 presents the top ten most highly cited publications on design for construction safety (DFS). The most cited article is "Linking construction fatalities to the design for construction safety concept" [50,51], published in the journal Safety Science in 2005, which has been cited 231 times. The research demonstrated a strong correlation between construction fatalities and the concept of design for construction safety and indicated an effective intervention that should be utilized and improved to enhance construction site safety.

Table 5. The top ten most frequency cited publications.

Rank	Author	Year	Title	Journal	Total Citations
1	Michael Behm	2005	Linking construction fatalities to the design for construction safety concept	Safety Science	231
2	Zhipeng Zhou, et al.	2015	Overview and analysis of safety management studies in the construction industry	Safety Science	198
3	John A. Gambatese, et al.	2015	Design's role in construction accident causality and prevention: Perspectives from an expert panel	Safety Science	152
4	Sijie Zhang, et al.	2015	Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis	Automation in Construction	138
5	John A. Gambatese, et al.	2005	Viability of designing for construction worker safety	Journal of Construction Engineering and management	123
6	Jonathan M. Samet, et al.	2003	Indoor environments and health: Moving into the 21st century	American Journal of Public Health	78

Table 5. *Cont.*

Rank	Author	Year	Title	Journal	Total Citations
7	B.H.W. Hadikusumo, et al.	2004	Capturing safety knowledge using design-for-safety-process tool	Journal of Construction Engineering and management	77
8	B.H.W. Hadikusumo, et al.	2002	Integration of virtually real construction model and design-for-safety-process database	Automation in Construction	75
9	T. Michael Toole	2005	Increasing engineers' role in construction safety: Opportunities and barriers	Journal of Professional Issues in Engineering education and practice	62
10	J.W. Seo, et al.	2008	Risk-based safety impact assessment methodology for underground construction projects in Korea	Journal of Construction Engineering and Management	51

The article cited second is "Overview and analysis of safety management studies in the construction industry", written by Z. Zhou. The eight articles ranked third to tenth are all about construction safety and construction safety. These articles focus on how to increase the health and safety of workers during in the construction process through engineers.

3.3.2. Highly Cited Author Analysis

Shown in Table 6 are the 12 most cited authors regarding DFS, along with centrality and their count. Among them, John A. Gambatese (31 counts) ranks first, followed by Michael Behm (30 counts), J. Hinze (18 counts), T. Michael Toole (15 counts), and Matthew R. Hallowell (14 counts). It is noteworthy that eight of the top twelve authors are based in the United States, indicating that the country places significant emphasis on human life safety.

Table 6. The top ten most frequently cited authors.

Rank	Count	Centrality	Country	Cited Authors
1	31	0.09	USA	John A. Gambatese
2	30	0.11	USA	Michael Behm
3	18	0.05	USA	J. Hinze
4	15	0.02	USA	T. Michael Toole
5	14	0.02	USA	Matthew R. Hallowell
6	12	0.10	USA	J. Wang
7	11	0.01	UK	A. Gibb
8	11	0.07	Thailand	B.H.W. Hadikusumo
9	10	0.00	USA	Sijie Zhang
10	8	0.01	USA	R.T. Szymberski

3.4. Research Hotpots

3.4.1. Overall: Keywords

Figure 6 presents a visualization of the co-occurrence of keywords in literature related to DFS between 2008 and 2018. The graph shows that the darker dots are significantly less than the green, light green and yellow dots, thus showing that the keywords safety, safety design and construction are becoming more frequent in the literature over time.

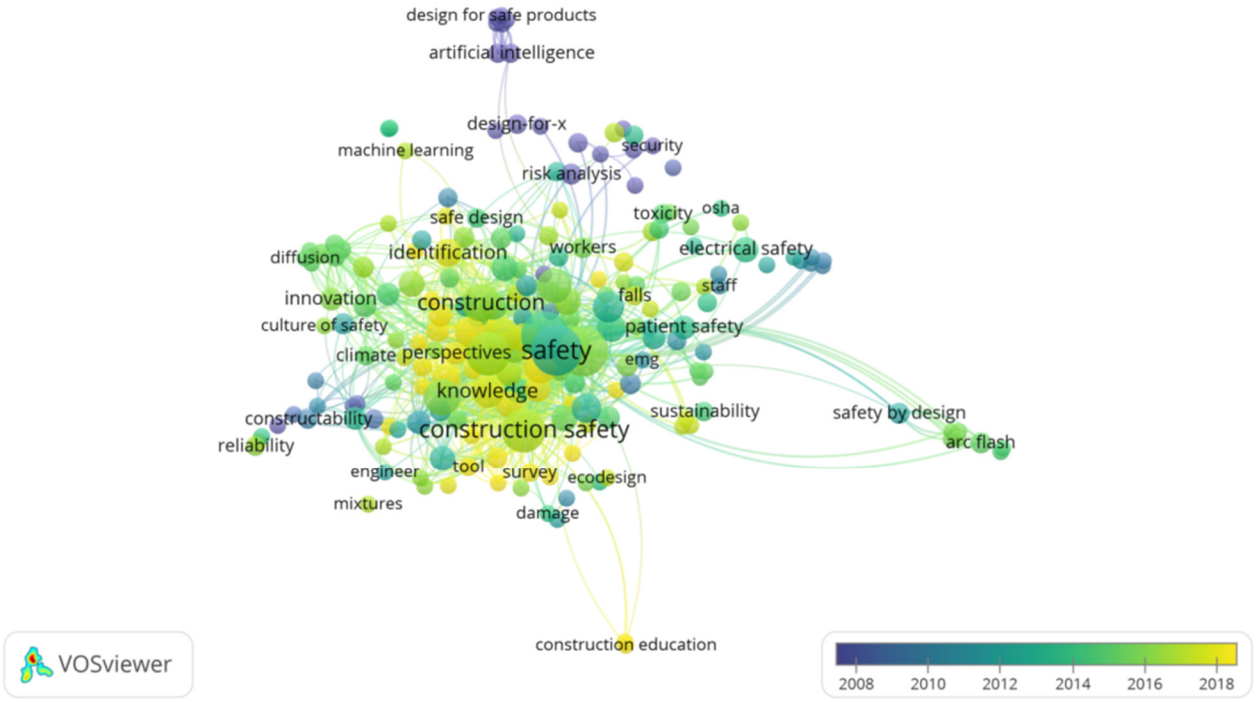


Figure 6. Co-occurrence of keywords based on time line.

Figure 7 shows a timeline view of the keyword clusters for the DFS publication, and it provides a more visual representation of how the keywords have changed over time. The log-likelihood ratio algorithm was used to aggregate 478 keywords and eight clusters were obtained. All clusters are marked by index entries extracted from the keywords. The largest cluster (#0) was labeled as "prevention through design", followed by the second largest cluster (#1) labeled as "risk management", and the third largest cluster (#2) was labeled as "construction industry". These clusters were also displayed in a timeline view.

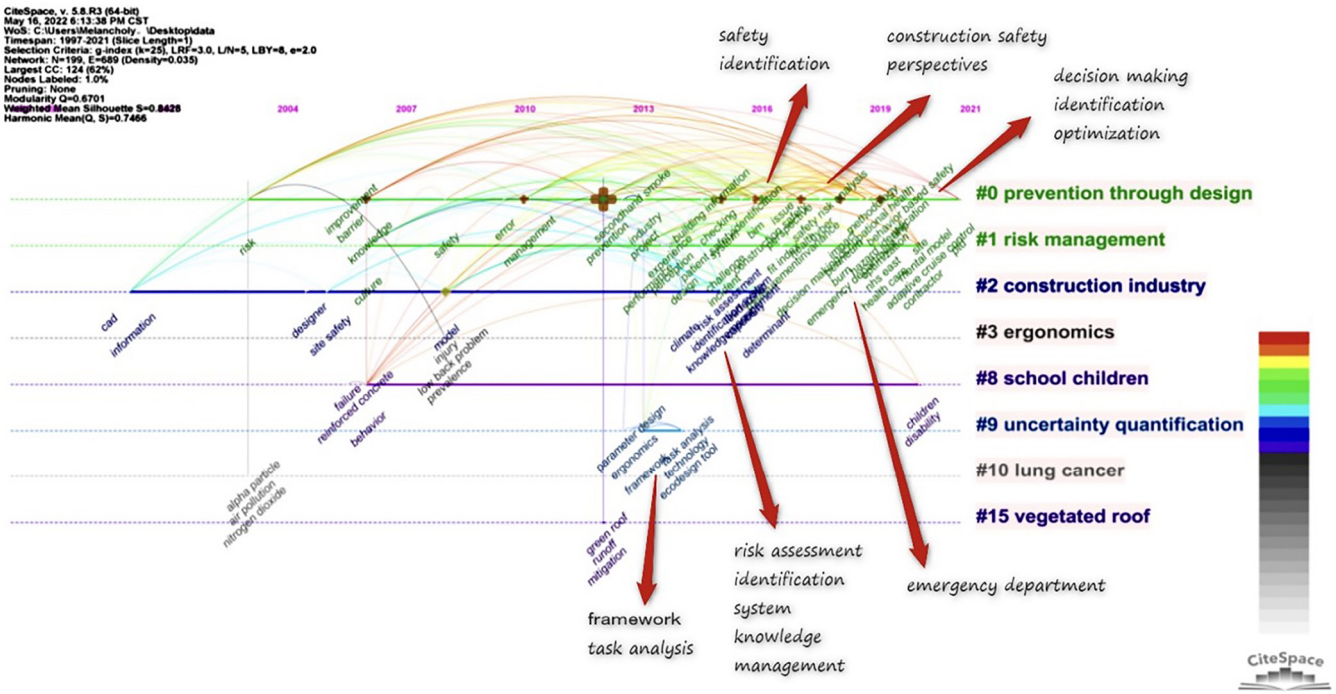


Figure 7. The timeline view of keyword clusters of publications.

3.4.2. Co-Citation Clustering: Keywords

Figure 8 shows the keyword co-citation clustering, network visualization, which groups closely related words into one category, that is, the same color in the figure below is a category, and the circles and labels form an element, the size of the visualization of the network is influenced by various factors such as the degree of the nodes, the strength of the connecting lines, and the number of citations.

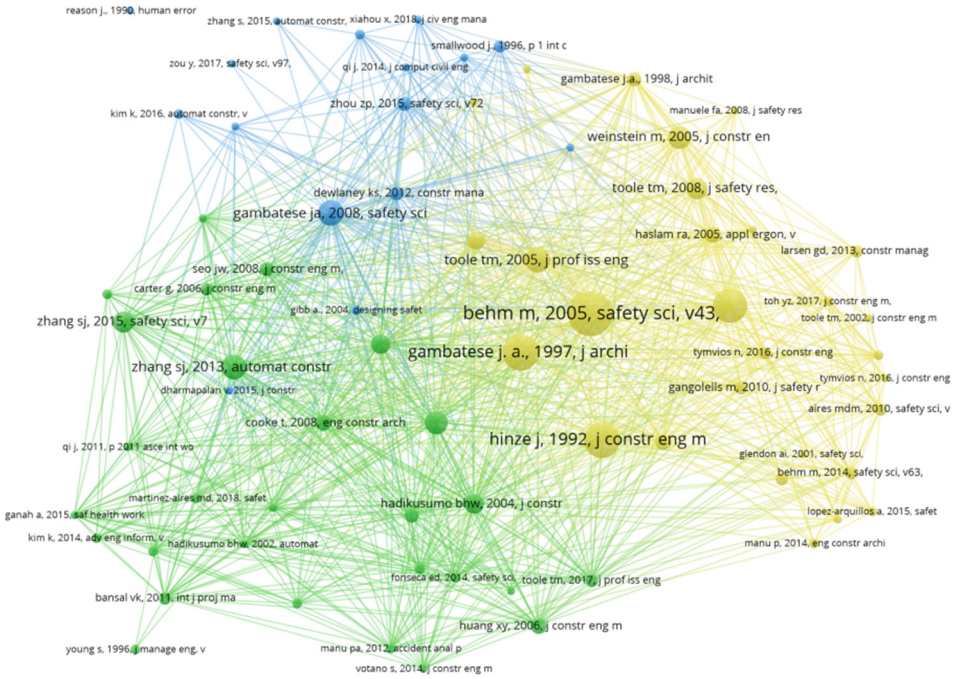


Figure 8. Co-citation clustering of keywords.

This visualization shows that the cited articles are divided into three categories, category 1 with the themes of building safety, safety design, and safety tools, category 2 with the themes of safety models, safety knowledge, and building information, and category 3 with the themes of causality, prevention, and safety management. It can be seen that the article "Linking construction fatalities to the design for construction safety concept" written by M. Behm on the topic of construction safety is one of the most frequently cited articles related to safety design.

3.5. Burst Detection

3.5.1. Burst Literature

Table 7 presents the 20 publications with the maximum “leading trend” in the acquired data. The sudden increase in citations for these publications indicates that they have attracted significant attention during a particular period and may have contributed to the advancement of the field.

Table 7. The top 20 references with the strongest citation bursts of DFS publications.

References	Year	Strength	Begin	End	1997–2021
E. Henley, 1992, Probabilistic Risk A, V0, P0	1997	3.7138	1997	1999	
Michael Behm, 2005, SAFETY SCI, V43, P589	1997	5.1535	2008	2013	
P.A. Schulte, 2008, J SAFETY RES, V39, P115	1997	6.2641	2011	2016	
M.D.M. Aires, 2010, SAFETY SCI, V48, P248	1997	3.16.4	2012	2018	
John A. Gambatese, 2008, SAFETY SCI, V46, P675	1997	7.6326	2013	2016	
T. Michael Toole, 2008, J SAFETY RES, V39,P225	1997	6.4034	2014	2016	
V.K. Bansal, 2011, INT J PROJ MANAG, V29,P66	1997	2.8166	2014	2015	
Sijie Zhang, 2013, AUTOMAT CONSTR, V29, P183	1997	4.0134	2014	2020	
W. Zhou, 2012, AUTOMAT CONSTR, V22, P102	1997	4.2501	2014	2016	
M. Gangolells, 2010, J SAFETY RES, V41, P107	1997	4.4858	2015	2018	
Matthew R. Hallowell, 2009, J CONSTR ENG M ASCE, V135, P990	1997	2.8838	2015	2017	
S. Rajendran, 2013, PRACT PERIOD SREYCT, V18, P67	1997	3.5197	2017	2020	
Y.M. Goh,2016, ACCIDENT ANNL PREV, V93, P260	1997	3.9286	2017	2020	
K.S. Dewlaney,2012, CONSTR MANAG ECON, V30, P165	1997	2.937	2017	2020	
Matthew R. Hallowelll,2016, SAFETY SCI, V82, P254	1997	4.9266	2017	2020	
M. Tymvios, 2016, J CONSTR ENG M, V142, P0	1997	3.9286	2017	2020	

Table 7. *Cont.*

References	Year	Strength	Begin	End	1997–2021
A. Lopez-Arquillos, 2015, SAFETY SCI, V73, P8	1997	3.2669	2017	2020	
N. Tymvios, 2016, J CONSTR ENG M, V142, P0	1997	2.8969	2018	2020	
Zhipeng Zhou Zhou, 2015, SAFETY SCI, V72, P337	1997	2.8969	2018	2020	
Y.Z. Toh, 2017, J CONSTR ENG M, V143, P0	1997	2.8969	2018	2020	

The main literature of the first twenty publications focuses on the research of safety design of construction engineering. For example, Michael Behm (2005) "Linking construction fatalities to the design for construction safety concept" (Ranked second), John A. Gambatese; Michael Behm (2008) "Design's role in construction accident causality and prevention: Perspectives from an expert panel" (Ranked fifth), and Martínez-Aires et al. (2010) "Prevention through design: The effect of European Directives on construction workplace accidents" (Ranked fourth) all touched this topic through various perspectives. These groundbreaking publications began to be cited after 2012, which shows that DFS has produced a series of innovative ideas and deeply penetrated considerable factors that affect safety design and life safety, such as forming fellowships with research workers and local building managers, sharing resources, and interflowing ideas and expertise with each other.

Schulte et al. (2008) "National prevention through design initiative" (Ranked third). Gangolells et al. (2010) "mitigated construction safety risks using prevention through design" (Ranked tenth), and Delaney & Hallowell (2012) "Prevention through design and construction safety management strategies for high-performance sustainable building construction" (Ranked 14th) all are all related to prevention by design to reduce safety risks.

Hallowell et al. (2016) "Exploring the fundamental causes of safety challenges faced by Hispanic construction workers in the US using photo-voice" (Ranked 15th) leveraged photovoice to explore the problems at construction sites to identify the root causes of construction worker safety challenges and thereby address the root causes of construction worker safety hazards.

3.5.2. Burst Keywords

As shown in Table 8, the strongest strength of the top 20 keywords in the DFS and their kinetic evolution from 1997 to 2020. Clearly, before 2013, the hot spots of DFS were primarily related to more abstract topics, such as expert systems, methodical design, design-for-x, and risk analysis. Since 2013, researchers' focus on DFS has shifted to more specific topics, including prevention through design, construction management, arc flash, industry, construction safety, and BIM. More specific keywords also show that the literature has more in-depth research on DFS. In sum, through the analysis of burst keywords and burst literature, the evolution process of DFS is obtained. First, the characteristics of the overall research have shifted from the design of the macro framework to the research of the micro-content. The research on DFS was more inclined to judge the results early. With the development of society, researchers turn their attention to more specific contents and the beginning of DFS, such as paying attention to construction management, and safety, preventing accidents through design, and paying attention to workers' health problems.

Second, the evolution of DFS research reflects the improvement of human self-security awareness. For example, in January 2020, the Shanxi gold mine explosion immediately triggered academic debate and attracted national attention. The accident caused 22 people to be trapped, including 10 deaths, one missing person, and 11 rescued, with a direct economic loss of 68.4733 million yuan. The investigation found that the main reason for the accident was the confusion of construction process management and inadequate safety design. Similar construction safety accidents occur frequently. To meet these challenges, the State Administration of Work Safety and the State Administration of Coal Mine Safety released a series of plans to explore how safety design can help reduce the occurrence of safety accidents in the procedure of building management. As a result, safety in the construction and maintenance process has gained increasing attention, and significant security events have marked the progression of DFS studies in recent years.

Table 8. Top 20 keywords with the strongest citation bursts of DFS publications.

Keywords	Year	Strength	Begin	End	1997–2021
expert system	1997	1.9396	1999	2001	
methodical design	1997	1.8305	2000	2004	
design-for-x	1997	1.9731	2000	2001	
risk analysis	1997	1.9733	2004	2010	
ergonomics	1997	2.951	2008	2013	
prevention through design	1997	2.0858	2013	2017	
model	1997	1.8832	2014	2016	
construction management	1997	1.8576	2014	2016	
arc flash	1997	1.8576	2014	2016	
design	1997	1.8317	2015	2020	
system	1997	2.1051	2015	2016	
industry	1997	2.2751	2015	2017	
innovation	1997	1.8376	2015	2016	
management	1997	3.0308	2016	2020	
construction safety	1997	3.2816	2016	2020	
BIM	1997	2.788	2016	2020	
health	1997	2.9778	2017	2020	
prevention through design	1997	2.891	2018	2020	
impact	1997	2.5072	2018	2020	
prevention	1997	3.1308	2018	2020	

3.5.3. Keyword Co-Occurrence and Co-Citation Clustering

The purpose of the keyword co-occurrence and co-citation cluster diagram is to determine the core topics and structures related to DFS research. Through visualization and statistical analysis, the clustering pattern is divided into the following four dimensions: purpose, people, procedure, and phenomena.

The "purpose" dimension describes the ultimate practical significance of DFS research and its objectives. The relevant issues in the cluster include keywords: safety, safety, design, building, safety, and performance. The documentation in this cluster primarily focuses on issues associated with building safety, health, and performance. This cluster is a tangible assessment of the performance of DFS due to a specific topic. This dimension mainly describes that the application of DFS in construction projects can strengthen project safety production and make sure the safety of human life and assets. In the construction process, the use of scientific methods, technologies, and means standardizing labor behavior, controlling labor objects, and the construction environment can eliminate and reduce many safety factors, making the construction production system composed of people, things, and environment reach the best safety state, and finally achieve the safety goal. Ensuring project safety is of practical significance for consolidating social security and providing an essential stable political setting for national economic development. It serves an important function in protecting workforce productivity and developing the economic labor force of various departments and industries in a balanced manner. It has a genuine economic impact on the accumulation of social wealth and the reduction of economic losses. For manufacturing personnel, it involves personal life, safety, and health, as well as the well-being and quality of life of the family.

The "people" dimension refers to the targets or specific groups within the scope of buildings or other facilities studied by DFS. The main studies in this cluster focused on workers in construction sites, employees in hydro-power construction, employees in dangerous workshops, and other industries involving dangerous work. The most fundamental and challenging issue to achieve the pursuit of safe design is the worker population and the construction and maintenance field. Construction workers, plumbers, and electricians, and employees in hazardous workshops (e.g., those working in hazardous environments) are typical populations that require special attention. Safety design, relying on optimizing tools and equipment in construction projects, could increase the safety of staff working process and timely protect the life safety of target groups and human health. In construction sites, workers are always facing health threats. Strengthening contact with the management of construction sites does help to obtain information, resources, and work details. This helps to provide detailed ideas for safety design, make the design more practical, and improve the safety factor. As the safety of the project is related to personal health, social harmony, and national security, it is urgent to pay attention to the project safety, the details in the construction process, and design everything related to the project for safety, to ensure the project safety and workers' safety.

The "procedure" dimension involves the knowledge, methods, and specific measures of the safety design basis. The relevant issues in the cluster include keywords: design prevention, design, prevention, inspection, decision-making, risk assessment, model, knowledge, prevention through design, and management. These keywords reflect the core methods of DFS. In other words, DFS currently emphasizes design prevention and adopts qualitative methods. The project manager is still the core provider to ensure project safety and worker safety. In buildings or other facilities projects, safety is regarded as the top priority, and safety design plays an important role. Although in recent years, there have been many safety-oriented designs, there are still great potential safety hazards in the buildings or other facilities field. Risk evaluation and risk assessment provide a weak flash for project safety. In the process of risk prevention, we should fully understand the details of the building and construction, and fully discuss the specific causes and details of the accident with the project manager. Determining how to solve or mitigate the occurrence

of major accidents through an effective and appropriate design is the guarantee for the smooth implementation and development of the project.

The "phenomena" dimension describes the current problems, impacts, and specific hazards of DFS research. The present literature of this cluster mainly focuses on topics related to accidents, chaos, and hazards in buildings or other facilities. At present, there are still great problems in China's construction safety, and not a few people are affected. The ultimate goal of DFS is to ensure that everyone is safe, which includes preventing accidents, minimizing harm to individuals, and addressing potential safety hazards in construction projects. This goal reflects the humanitarian and humanistic principles that life safety should be equal for everyone. As the safety of human lives and property and the overall sustainable development of the national economy and social stability are closely tied to project safety, there is an urgent need to strengthen construction safety measures.

4. Discussion

Through a bibliometric analysis based on the WoS database, this paper examines global research findings related to "design for safety" and offers possible ways to improve safety performance in the construction industry. The 4P model of purpose, people, procedure, and phenomenon is used to explore the results of the bibliometric analysis and its implications.

In the purpose dimension, this paper explores the importance of safety design, i.e., ensuring the safety of human life and building quality in the construction field and guaranteeing normal production order. Through the bibliometric analysis, we found that research on safety design has been conducted all over the world and the research results have been widely noticed and applied. Safety design is one of the important methods to improve safety performance in the construction industry, and there is a need to strengthen related research and explore new safety design methods and theories in the future. In addition, research on risk assessment and risk control needs to be strengthened to achieve more detailed and comprehensive safety design.

In the people dimension, this paper focuses on researchers and developers of safety design. Through bibliometric analysis, we found that safety design relies on engineers, architects, and experts in related fields. The role of researchers is crucial here, as they need to provide an in-depth understanding of the target population and their needs to provide feasible safety design solutions to ensure the effectiveness and feasibility of safety design. In the future, the field of architecture or other facilities should strengthen the training and construction of safety design talents.

In the procedural dimension, this paper analyzes the basics, methods and specific measures of safety design. The implementation of safety design needs to be centered on prevention, using qualitative methods and technology to ensure that the safety and health risks of personnel are effectively controlled. In the future, the use of technologies such as artificial intelligence and big data analysis should be enhanced to improve the accuracy and feasibility of safety design.

In the phenomenal dimension, this paper discusses the impact of current safety hazards and accidents on project quality, life and property safety of personnel and project schedule. There is an urgent need to strengthen the research on construction safety measures, including risk assessment and risk control, in order to reduce the occurrence of accidents and ensure the stable implementation of projects.

This paper assesses the results of global research on "safety by design" through a bibliometric analysis and suggests possible ways to improve safety performance in the construction industry. Based on the findings, this paper suggests that future research should focus on the following areas:

1. Strengthen the application of artificial intelligence and big data technology in safety design to improve the accuracy and feasibility of safety design.
2. Strengthen research on the practice and effects of safety design in different types of construction projects, expand the sample scope, and explore the actual effects in different application scenarios.

3. Strengthen the research on safety measures, explore in depth the details of risk assessment and risk control, and guarantee the safety of personnel during the project implementation process.
4. Strengthen the training and construction of safety design talents, and raise the importance of safety design among engineers, architects and experts in related fields.
5. Strengthen the research of basic theories and methods related to safety design, including in-depth discussions on safety risk management and engineering safety management.

Overall, the research findings of this paper provide some reference and guidance for future research directions and priorities regarding safety design. Future research should be conducted in depth around the above recommendations to promote a safer, more efficient and sustainable development of the construction industry. This is also the guiding direction for this study to carry out in future research.

5. Conclusions

The purpose of this paper is to provide a comprehensive assessment of the trends in DFS in the construction industry. The results of the study indicate that DFS has become an effective method for improving building safety, in addition to the following key findings of this study.

First, a bibliometric analysis reveals that DFS research has shown a rapid growth trend and is receiving a lot of attention worldwide. Second, the findings demonstrate that DFS has become an effective method for reducing life-cycle risk in the construction industry, but it is not the only factor that can influence safety issues. In addition, this paper provides a comprehensive analysis of DFS trends in terms of authors, journals, institutions, countries, co-citations, and co-occurrence.

Over the past 24 years, the field of DFS has experienced significant growth, particularly since 2017. During this time, numerous academics and organizations have contributed to the scientific progress of DFS. To analyze the evolution of the literature, we conducted a bibliometric analysis based on 210 articles and their 1908 references. We analyzed authors, journals, institutions, countries, co-citations, and co-occurrences to provide a holistic picture of DFS research.

The results of the study show that DFS, although not the only factor influencing safety, is a viable method of improving safety performance in construction industry. The UK accident rate in 2005 was 17.4% lower than when DFS was first implemented in 1995. In Singapore, the workplace fatality rate, which was 4.9 per 100,000 in 2004, also reduced to 1.9 per 100,000 in 2015. There is no doubt that DFS has become an effective method of reducing life cycle safety risks for all project undertakings.

The contributions of this paper to the DFS theory include (1) proposing the concept, principle and application method of DFS, which provides a new research perspective and method for safety issues in the construction field; (2) providing data support for improving safety in the construction industry through bibliometric analysis, which provides a new way of thinking for safety management in the construction industry.

In brief, DFS has entered a phase of rapid growth and is attracting worldwide attention. However, there are some limitations of this article. For instance, our use of a WoS-based database may have missed some relevant articles, and the use of different metrics and mapping methods may impact the results. In the study of this paper, we mainly used the Web of Science database for literature search. Although Web of Science is one of the world's leading academic databases and contains a large number of journals and conference papers related to the field of architecture, we also recognize that using a single database for the search can have certain limitations and biases. In order to obtain a more comprehensive understanding of the research in our field, we also consulted other databases such as Scopus and Google Scholar, and obtained as much of the literature related to the field of architecture worldwide as possible. However, due to limitations such as time and resources, we were unable to cover all possible literature sources, which also led to the

possibility of some bias in our bibliometric findings. Therefore, we will try to use more databases for literature search and employ multiple literature search methods to minimize bias in our future research. Moreover, we will fully discuss the limitations of the literature search in our study so that readers can have a more comprehensive understanding of our findings. Nonetheless, our study provides important insights into DFS trends and may inform future research.

Overall, the development of DFS has helped us better focus on personnel safety issues, construction safety issues, and operational stage safety issues. We hope that our findings will encourage further research in this area and ultimately lead to even greater improvements in project life cycle safety.

Based on the research in this paper, we propose the following suggested possible future research topics:

To study the situation and effects of DFS in different types of construction projects in order to better understand the practical applications and effects of DFS in various construction projects and to provide targeted suggestions for further improving construction safety.

To study the application and effectiveness of DFS in other industries in order to better understand the application prospects and potential of DFS in different industries, and to provide more detailed information and evidence for expanding the scope of DFS applications.

To study how to effectively apply DFS to different phases of project lifecycle, so as to better understand the effectiveness and optimization methods of DFS application in different phases of projects, and provide targeted suggestions for more comprehensive project security improvement.

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Abbreviations

DFS	Design For Safety
WoS	Web of Science
4P	Purpose, People, Procedures, and Phenomena

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