



INTERNATIONAL JOURNAL OF
INNOVATION AND
INDUSTRIAL REVOLUTION
(IJIREV)

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DESIGN FOR SAFETY (DFS) IN EDUCATION FOR CONSTRUCTION: A BIBLIOMETRIC ANALYSIS

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Article Info:

Article history:

Received date: 02.04.2026

Revised date: 15.04.2026

Accepted date: 31.05.2026

Published date: 22.06.2026

Abstract:

Design for Safety (DfS) has emerged as a critical approach in the construction industry to eliminate or minimize occupational hazards through informed design decisions proactively. Despite increasing recognition of DfS principles, the integration of DfS into construction education and curriculum development remains fragmented and underexplored in the existing literature. Limited studies have systematically examined the intellectual structure, research evolution, and collaborative patterns of DfS in educational contexts, thereby constraining the development of comprehensive pedagogical frameworks for future construction professionals. Accordingly, this study aims to conduct a comprehensive bibliometric analysis of global research trends related to DfS in education for construction. Bibliographic data were systematically retrieved from the Scopus database. The retrieved dataset was subsequently refined and

To cite this document:

Ismail, F., Kamaruddin, T., Mohd, N. I., Ariffin, H. L. T., Shukery, N. M., Abd Wahid, S. N., Shollunayagam, R. M. (2026). Design For Safety (Dfs) In Education for Construction: A Bibliometric Analysis. *International Journal of Innovation and Industrial Revolution*, 8(25), 183-200.

standardized using OpenRefine to ensure data consistency and accuracy prior to analysis. Scopus Analyzer and VOSviewer software were employed to examine publication trends, citation structures, keyword co-occurrence patterns, and country-level collaboration networks. Following the screening and refinement process, a total of 744 relevant publications were identified and analysed. The findings reveal a substantial increase in publication output after 2015, indicating growing scholarly attention toward integrating safety-oriented design principles into construction education. Keyword co-occurrence analysis further identified dominant research themes in construction, health and safety, construction safety, Building Information Modeling (BIM), virtual reality, and prevention through design, reflecting the increasing influence of digital technologies and Industry 4.0 in safety education. In addition, country-level collaboration analysis demonstrated that the United States and the United Kingdom remain the leading contributors to Dfs educational research. Overall, this study provides a comprehensive overview of the intellectual development, thematic evolution, and global research landscape of Dfs in construction education, offering valuable insights for researchers, educators, policymakers, and industry practitioners seeking to advance proactive safety integration within construction curricula and professional training.

DOI: 10.35631/IJIREV.825011

Keywords:

Construction, Dfs, Education, SbD



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Introduction

Educational institutions at all levels are increasingly seen as key sites for shaping how future professionals understand and act on safety. Across engineering; health; and school-based Science, Technology, Engineering, and Mathematics (STEM), there is a growing move from treating safety as a regulatory afterthought toward designing by safety, embedding safety thinking directly into design, curriculum, and professional identity (Behm et al., 2014; Foley et al., 2016; Ibrahim et al., 2022; Qian et al., 2023; Van Gelder et al., 2021). This orientation aligns with broader agendas such as sustainability, public welfare, and responsible innovation (Ibrahim et al., 2022; Sandri et al., 2022; Van Gelder et al., 2021). The following overview situates “Design by Safety in Education” within these evolving research and practice trends.

Design for Safety (Dfs) or Safety by Design (SbD) seeks to anticipate and minimize hazards early in the design process, making safety an inherent design requirement rather than an add-on (Bouchaut & Asveld, 2025; Foley et al., 2016). Reviews across engineering disciplines show that SbD functions as a specific form of responsible innovation, balancing safety with values such as sustainability, equity, and affordability (Ibrahim et al., 2022). In construction, Dfs is framed as integrating worker health and safety at the front end of the project lifecycle and has

generated substantial research on concepts, management, technology, capability, education, and sustainability (Behm et al., 2014). In chemical and process engineering, prevention through design and process safety frameworks similarly emphasize inherent, passive, active and procedural safety strategies within core equipment and process design activities (Gunasekera et al., 2019; Misnan et al., 2017). Collectively, this literature provides the conceptual backbone for a “design by safety” approach in education.

Other than that, multiple studies highlighted that graduates often lack adequate knowledge of safety legislation, risk management and design responsibilities, revealing gaps in existing curricula (Azmi & Misnan, 2022). In engineering, safe design is recognized as essential yet inconsistently embedded, with calls to ensure it is presented as an inherent user requirement in all design models taught to students (Jamieson et al., 2020; Misnan et al., 2017). In construction-related programs, academics generally support integrating DfS but note that current curricula provide only minimal intervention and are insufficient to prepare graduates for zero-accident goals (Azmi & Misnan, 2022; Bouchaut & Asveld, 2025). Health professions indicate parallel dynamics: quality and safety education frameworks for nurses and patient safety education for medical and nursing students have expanded rapidly. Nonetheless, there remains a lack of systematic, globally consistent approaches and limited penetration into practice and outcome-focused research (d’Entremont & Merryweather, 2018; Wang et al., 2024; Zhou et al., 2024). These trends support the argument that design-by-safety principles must be intentionally structured into program outcomes, content, and assessment rather than left to informal or ad hoc coverage.

A central question in the literature is *how* to integrate safety into curricula: as standalone courses, embedded content, or hybrid models. Studies of DfS and design safety identify at least four strategies: (1) creating new degrees or courses; (2) adding specific safety subjects; (3) embedding cross-cutting safety topics across multiple courses; and (4) incorporating safety expectations into capstone design projects (Misnan et al., 2017; Zhou et al., 2024). Surveys of academics in architecture and civil engineering indicate support for both standalone and embedded approaches, with a slight preference for embedding. Note that recognition that limited staff expertise can undermine embedded strategies if not accompanied by targeted capacity-building (Azmi & Misnan, 2022; Bouchaut & Asveld, 2025). In chemical engineering, case-based and project-based frameworks integrate safety strategies into equipment design, with students reporting positive learning of inherent and procedural safety through such activities (Misnan et al., 2017). Similarly, interventions using case studies and structured analytical tools have been demonstrated to shift engineering students’ thinking from “safe people” toward “safe place” and to increase their use of the hierarchy of controls in design (Gunasekera et al., 2019; Pollock & Sørensen, 2021). In pre-university STEM and engineering design courses, standards and state safety guides increasingly weave safety concepts throughout design-based learning expectations, reinforcing safety as a foundational condition for experiential learning (Love, 2024; Love et al., 2023; Sherwood et al., 2023).

Recent work emphasized that safety education must move beyond technical compliance toward broader capabilities for public safety, sustainability, and ethical decision-making. In engineering, interviews with pipeline engineers show strong synergies between safety and sustainability capabilities, suggesting that safety learning can be contextualized within sustainability education to better prepare graduates for complex professional environments (Van Gelder et al., 2021). Bibliometric analyses in patient safety and nursing education reveal major research hotspots around simulation, communication, interprofessional collaboration,

and assessment of safety competencies, signalling a shift toward active, practice-oriented pedagogies (Zhou et al., 2024; Zain et al., 2025). The concept of “Safety Education 4.0” in chemical engineering proposes project-based learning, co-taught by academics and industry, to align safety competence with Industry 4.0 technologies and real industrial demands (Qian et al., 2023). At the school level, national studies of P–12 engineering and technology educators highlighted that comprehensive safety training and structured safety policies significantly reduce accident odds, underscoring the importance of formal safety preparation for teachers as part of design-based instructional competence (Love et al., 2023; Sherwood et al., 2023). Across contexts, there is a growing emphasis on critical reflection, ethics, and value-sensitive design to help learners navigate trade-offs and integrate safety meaningfully into design decisions (Gunasekera et al., 2019; Ibrahim et al., 2022; Pollock & Sørensen, 2021).

Across engineering, health and P–12 STEM, the literature converges on the need to treat safety as a core design and educational value rather than a peripheral constraint. SbD and DfS provide conceptual frameworks that, when translated into curriculum outcomes, pedagogies and institutional structures, can cultivate graduates who approach all design work with safety as an inherent requirement. Moreover, evidence supports mixed strategies. Standalone safety courses, embedded topics, capstone integration and authentic case- and project-based learning while also highlighting the need to develop educator expertise and align with broader agendas such as sustainability and responsible innovation (Behm et al., 2014; Foley et al., 2016; Ibrahim et al., 2022; Qian et al., 2023; Love et al., 2023; Love & Roy, 2024). A DfS approach in education, therefore, is not only about reducing accidents. It is also about shaping professionals and citizens capable of responsibly addressing complex socio-technical risks throughout their careers.

Research Question

1. How has the scholarly publication output on DfS in education evolved between 1935 and May 2026?
2. Which publications have exerted the greatest scholarly influence in DfS in education research based on citation impact?
3. What are the prevailing and emerging thematic trends in DfS research within education, as revealed through keyword co-occurrence analysis?
4. What patterns of international scholarly collaboration characterize DfS research in education, as evidenced by country-level co-authorship networks?

Methodology

Bibliometric analysis refers to the systematic acquisition, classification, and quantitative evaluation of bibliographic information derived from scholarly publications (Alves et al., 2021; Assyakur & Rosa, 2022; Verbeek et al., 2002). In addition to conventional descriptive indicators such as publication outlets, chronological publication patterns, and leading contributors, bibliometric approaches incorporate advanced analytical techniques, including document co-citation analysis, to elucidate the intellectual architecture, thematic evolution, and knowledge diffusion within a research domain (Wu & Wu, 2017). Conducting a rigorous literature review requires an iterative, methodologically structured process that involves refined keyword formulation, comprehensive database retrieval, and critical analytical interpretation. This systematic framework supports the development of a robust bibliographic

corpus while enhancing the reliability, validity, and reproducibility of the findings (Fahimnia et al., 2015).

In this context, the present study emphasized high-impact scholarly publications, as these works provide substantial theoretical and conceptual insights that shape the field of research. To ensure data accuracy, consistency, and comprehensive disciplinary coverage, Elsevier's Scopus database was used as the primary source for bibliographic extraction (Al-Khoury et al., 2022; di Stefano et al., 2010; Khiste & Paithankar, 2017). Furthermore, to preserve the scholarly integrity and quality of the dataset, only peer-reviewed journal articles were included. In contrast, books, conference notes, and lecture materials were deliberately excluded (Gu et al., 2019). Accordingly, relevant publications published between 1939, and May 2026 were systematically retrieved from the Scopus database for subsequent bibliometric evaluation.

Data Search Strategy

The bibliometric dataset for this study was systematically retrieved from the Scopus database using a structured search strategy designed to capture publications on DfS education in the construction domain. The search query, as illustrated in Table 1, incorporated multiple synonymous terms and variations associated with the concept of DfS, including "Design by Safety," "DfS," "Safety by Design," and "SbD" combined with education-related keywords such as "Curricula," "Curriculum," and "Education," as well as the term "Construction." The search was performed using the TITLE-ABS-KEY function to ensure that the selected publications explicitly addressed the relevant concepts within the article title, abstract, or author keywords. This comprehensive retrieval strategy was adopted to maximize the inclusiveness and relevance of the bibliographic dataset while minimizing the omission of significant scholarly contributions within the research scope. The initial search yielded 744 publications from the Scopus database.

To ensure the reliability, consistency, and academic relevance of the retrieved dataset, a systematic screening process was subsequently conducted based on the selection criteria presented in Table 2. Only publications written in English were included to maintain linguistic consistency and facilitate accurate bibliometric interpretation, while non-English publications were excluded. In terms of subject classification, the study focused exclusively on publications indexed in the Social Sciences and Engineering fields, as these disciplines are closely related to construction education, safety management, and curriculum development. Consequently, publications outside these subject areas were excluded to preserve the dataset's thematic relevance and analytical precision. The application of these inclusion and exclusion criteria refined the bibliographic corpus, ensuring that the final dataset accurately represented the intellectual landscape of DfS education research within the construction sector.

Table 1: The Search String

Scopus	(TITLE-ABS-KEY (Design for Safety) OR TITLE-ABS-KEY (DfS) OR TITLE-ABS-KEY (Safety by Design) OR TITLE-ABS-KEY (SbD) AND TITLE-ABS-KEY (Curriculum) OR TITLE-ABS-KEY (Curricula) OR TITLE-ABS-KEY (Education) AND TITLE-ABS-KEY (Construction)) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "SOCI"))
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Table 2: The Selection Criterion is Searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Subject	Social Sciences and Engineering	Others

Data Analysis

VOSviewer is a prominent bibliometric mapping and visualization software developed by Nees Jan van Eck and Ludo Waltman at Leiden University, the Netherlands (van Eck & Waltman, 2010, 2017). The software has been extensively adopted in bibliometric and scientometric research due to its robust capability to analyze and visualize complex scientific knowledge structures. Designed specifically for large-scale bibliographic analysis, VOSviewer enables the construction of network visualizations, thematic clustering, and density mapping, thereby facilitating a comprehensive examination of scholarly communication patterns and intellectual development within a research domain. The software supports diverse bibliometric analyses, including co-authorship, co-citation, bibliographic coupling, and keyword co-occurrence analyses, allowing researchers to identify collaborative structures, influential publications, and emerging thematic trends. Its interactive visualization environment, computational efficiency, and continuous methodological refinement further strengthen its utility as an advanced analytical platform for scientific research evaluation.

A major strength of VOSviewer lies in its ability to transform extensive, multidimensional bibliometric datasets into coherent, interpretable visual representations. Through network-based analytical techniques, the software effectively identifies thematic clusters, uncovers patterns of keyword co-occurrence, and visualizes the interconnectivity among authors, institutions, and research topics. The intuitive interface enhances analytical accessibility for both novice and experienced researchers, enabling systematic exploration of knowledge structures and the evolution of research. Furthermore, the software's adaptability to multiple bibliographic data formats and analytical configurations ensures its applicability across a broad spectrum of scientometric investigations.

In the present study, bibliographic records comprising publication year, article title, author information, source journals, citation counts, and author keywords were extracted from the Scopus database in PlainText format, covering publications published between 1939 and May 2026. The retrieved dataset was subsequently analyzed using VOSviewer version 1.6.20 to construct bibliometric networks and thematic clusters within the research field. By employing VOS mapping and clustering techniques, the software facilitated the visualization and interpretation of relationships among bibliometric entities. Unlike conventional Multidimensional Scaling (MDS), the VOS technique implemented in VOSviewer positions items in a low-dimensional space such that the proximity between items accurately reflects their relatedness (van Eck & Waltman, 2010). Although conceptually analogous to MDS (Appio et al., 2014), the VOS approach differs methodologically through the application of normalization procedures specifically optimized for co-occurrence data, particularly the Association Strength (AS_{ij}), which is mathematically expressed as follows (Van Eck & Waltman, 2007):

$$AS_{ij} = \frac{C_{ij}}{W_i W_j}$$

which is defined as the proportional relationship between the observed frequency of co-occurrence between items i and j and the expected frequency of their co-occurrence under the assumption of statistical independence between the two items (Van Eck & Waltman, 2007).

Result and Discussion

There are four research questions discussed in this section.

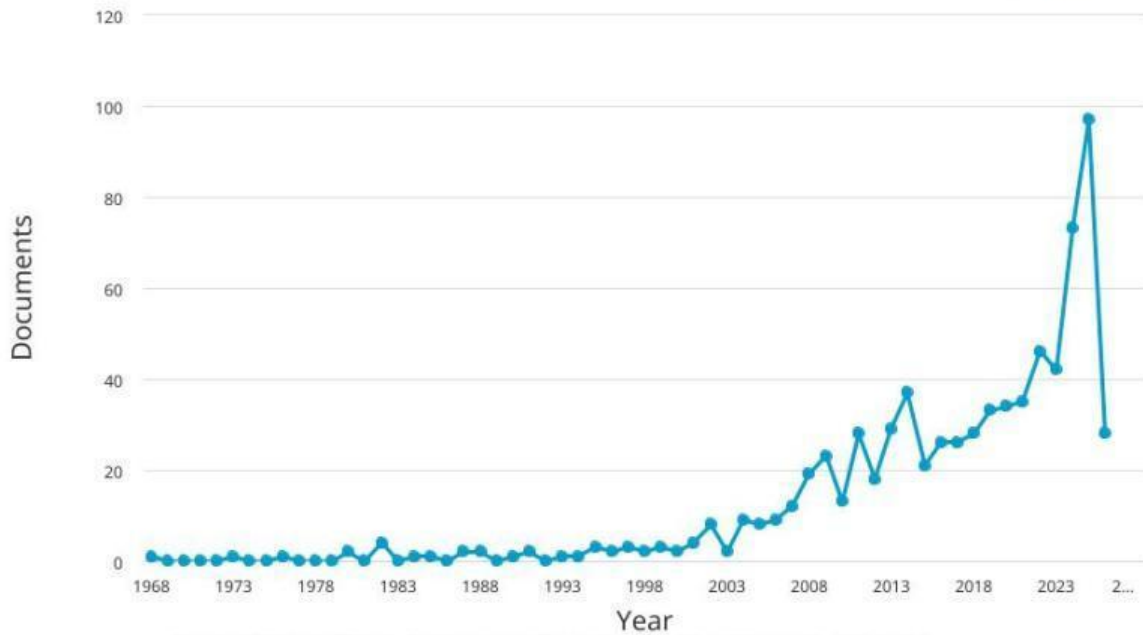
RQ1: How Has the Scholarly Publication Output on Design for Safety (Dfs) In Education Evolved Between 1935 And May 2026?

The temporal distribution of publications on DfS in education, as highlighted in Figure 1 and Table 3, demonstrates substantial and progressive growth in scholarly attention, particularly after the mid-2000s. Although the earliest identified publication dates back to 1939, research activity remained extremely limited for several decades, with annual publication output generally below 5 prior to 2000. This relatively low level of research productivity may be attributed to the limited recognition of safety-oriented design principles within educational frameworks during the early stages of industrial and construction development. During this period, safety management practices were predominantly reactive and operational, with limited emphasis on integrating safety considerations into design processes and educational curricula. Furthermore, the concept of DfS had not yet matured into a distinct academic and professional discourse, leading to fragmented, isolated scholarly contributions. A gradual increase in publication output emerged in the early 2000s, reflecting growing awareness of occupational safety, sustainability, and risk prevention within engineering and construction education. The expansion of international safety regulations, technological advancements, and industry demand for proactive safety competencies are likely contributing to the growing academic interest in DfS-related educational research.

A significant acceleration in publication growth is evident from 2014 onwards, culminating in the highest publication output in 2025 with 97 publications (13.0%), followed by 2024 with 73 publications (9.8%). This sharp upward trajectory indicates that DfS in education has evolved into an increasingly important and contemporary research domain. The intensified research activity may be associated with several interrelated factors, including the global emphasis on sustainable construction practices, digital transformation in the built environment, and heightened concern regarding workplace safety and accident prevention. In particular, the emergence of Industry 4.0 technologies, BIM, and smart construction systems has underscored the importance of integrating safety knowledge into engineering and construction curricula to prepare future professionals for complex, technology-driven project environments. Additionally, universities and accreditation bodies have increasingly recognized the need to embed safety-oriented competencies within higher education programs to align with industry expectations and regulatory requirements. The consistently high publication output observed between 2020 and 2026 further suggests that DfS education is transitioning from a niche research topic to a mainstream academic discourse, characterized by growing interdisciplinary collaboration and global scholarly engagement.

Documents by year

Scopus



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Figure 1: Trend of Research in DfS in Education by Years**Table 3: Number of Publications in DfS in Education by Years**

YE A R	Number of Publica tions	Percentag e (%)	YE A R	Number of Publica tions	Percentag e (%)
2026	28	3.8	2003	2	0.3
2025	97	13.0	2002	8	1.1
2024	73	9.8	2001	4	0.5
2023	42	5.6	2000	2	0.3
2022	46	6.2	1999	3	0.4
2021	35	4.7	1998	2	0.3
2020	34	4.6	1997	3	0.4
2019	33	4.4	1996	2	0.3
2018	28	3.8	1995	3	0.4
2017	26	3.5	1994	1	0.1
2016	26	3.5	1993	1	0.1
2015	21	2.8	1991	2	0.3
2014	37	5.0	1990	1	0.1
2013	29	3.9	1988	2	0.3
2012	18	2.4	1987	2	0.3
2011	28	3.8	1985	1	0.1
2010	13	1.7	1984	1	0.1

2009	23	3.1	1982	4	0.5
2008	19	2.6	1980	2	0.3
2007	12	1.6	1976	1	0.1
2006	9	1.2	1973	1	0.1
2005	8	1.1	1968	1	0.1
2004	9	1.2	1939	1	0.1

RQ2: Which Publications Have Exerted the Greatest Scholarly Influence in Design for Safety (Dfs) In Education Research Based on Citation Impact?

Table 4 presents the top 10 most cited publications in the field of Dfs in education and construction-related safety research, highlighting the intellectual foundations and influential research directions within the domain. The most highly cited article, authored by Park & Kim (2013) and titled “*A framework for construction safety management and visualization system,*” received 327 citations, indicating strong scholarly and industrial interest in integrating digital technologies into construction safety management. The dominance of publications from journals such as *Automation in Construction* demonstrates the growing convergence among safety management, technological innovation, and digital transformation in the construction sector. Similarly, studies focusing on Radio-Frequency Identification (RFID) systems, Virtual Reality (VR), and proximity hazard indicators achieved substantial citation impact, reflecting the growing importance of advanced technologies in enhancing safety training, hazard identification, and risk prevention. The prominence of these technology-oriented studies suggests that contemporary Dfs research has evolved beyond conventional safety management approaches toward data-driven, automated, and immersive safety solutions aligned with Industry 4.0 developments. Furthermore, highly cited review-based articles, such as Chen et al. (2022) and Alper & Karsh (2009), indicated that systematic and integrative studies are particularly influential because they provide comprehensive conceptual frameworks and synthesize emerging research trends to inform future scholarly development.

The citation patterns in Table 4 also reveal the enduring significance of foundational research on safety culture, worker behavior, and educational interventions in construction safety. For instance, the study by Wilkins (2011) on construction workers’ perceptions of health and safety training programs accumulated 249 citations, underscoring the critical role of education and training in improving safety performance and behavioral compliance. Likewise, the seminal work by Gambatese et al. (1997), “*Tool to design for construction worker safety,*” remains highly cited despite its earlier publication year, demonstrating its foundational contribution to establishing the Dfs concept within construction engineering discourse. The sustained influence of older publications indicates that Dfs research continues to build upon established theoretical and methodological frameworks while simultaneously incorporating emerging technologies and digital innovations. Additionally, the inclusion of interdisciplinary studies, such as research on social networking sites and Internet of Things (IoT) applications, suggests that Dfs education is increasingly shaped by cross-disciplinary perspectives involving communication technologies, human behavior, and smart systems. Collectively, these citation trends demonstrate that highly influential studies in the field are typically characterized by strong practical applicability, technological relevance, and the capacity to address evolving safety challenges within modern construction environments.

Table 4: Most Cited Authors

No	Authors	Title	Year	Source title	Cited by
1	Park & Kim (2013)	A framework for construction safety management and visualization system	2013	Automation in Construction	327
2	Livingstone & Brake (2010)	On the rapid rise of social networking sites: New findings and policy implications	2010	Children and Society	261
3	Wilkins (2011)	Construction workers' perceptions of health and safety training programs	2011	Construction Management and Economics	249
4	Kelm et al. (2013)	Mobile passive Radio Frequency Identification (RFID) portal for automated and rapid control of Personal Protective Equipment (PPE) on construction sites	2013	Automation in Construction	219
5	Chen et al. (2022)	Implementation of technologies in the construction industry: a systematic review	2022	Engineering, Construction and Architectural Management	192
6	Zhang et al. (2022)	Virtual reality technology in construction safety training: Extended technology acceptance model	2022	Automation in Construction	173
7	Alper & Karsh (2009)	A systematic review of safety violations in industry	2009	Accident Analysis and Prevention	159
8	Gambatese et al. (1997)	Tool to design for construction worker safety	1997	Journal of Architectural Engineering	150
9	Teizer & Cheng (2015)	Proximity hazard indicator for workers-on-foot near miss interactions with construction equipment and geo-referenced hazard areas	2015	Automation in Construction	135
10	Gamil et al. (2020)	Internet of things in construction industry revolution 4.0: Recent trends and challenges in the Malaysian context	2020	Journal of Engineering, Design and Technology	130

RQ3: What Are the Prevailing and Emerging Thematic Trends in Design for Safety (DfS) Research Within Education, As Revealed Through Keyword Co-Occurrence Analysis?

Figure 2 illustrates the keyword co-occurrence network generated using VOSviewer, highlighting the principal research themes and conceptual relationships within the field of DfS in education. The analysis revealed that the keywords “*construction*” and “*health and safety*” had the highest occurrence frequency (61 each), indicating that the research domain is strongly rooted in construction-related occupational safety concerns. The prominence of keywords such as “*construction safety*,” “*design for safety*,” and “*prevention through design*” further demonstrates that the literature predominantly emphasizes proactive safety integration during the planning and design stages rather than relying solely on reactive safety management practices. The strong total link strengths associated with “*construction*,” “*design for safety*,” and “*health and safety*” suggest that these concepts function as central nodes connecting multiple research clusters within the network. Furthermore, the frequent use of technology-oriented keywords, including “*VR*,” “*BIM*,” “*augmented reality*,” “*artificial intelligence*,” and “*digital twin*,” indicates a growing scholarly focus on integrating emerging digital technologies into safety education and training. This trend reflects the growing influence of Industry 4.0 and smart construction practices, in which immersive visualization tools and intelligent systems are increasingly used to enhance hazard recognition, experiential learning, and safety decision-making among construction professionals and students.

In addition, Figure 2 demonstrates that DfS education research is progressively expanding beyond conventional safety training toward broader educational, sustainability, and competency-oriented perspectives. The occurrence of keywords such as “*engineering education*,” “*construction education*,” “*education and training*,” and “*authentic learning*” suggests a strong emphasis on pedagogical innovation and competency development within construction and engineering curricula. This indicates that researchers increasingly recognize the importance of embedding safety knowledge and practical learning experiences into higher education programs to prepare future professionals for complex construction environments. Moreover, the emergence of sustainability-related terms, including “*sustainable development goal*,” “*sustainability*,” and “*circular economy*,” reflects the evolving alignment between DfS principles and global sustainability agendas, particularly in promoting safer, healthier, and more resilient built environments. The presence of contextual keywords such as “*developing countries*,” “*Malaysia*,” and “*construction workers*” further suggests growing scholarly attention toward region-specific safety challenges and workforce-related issues within emerging economies. Meanwhile, the relatively lower occurrence frequencies of advanced technological keywords, such as “*machine learning*” and “*digital twin*,” imply that these areas remain emerging research directions with substantial potential for future exploration. Collectively, the co-occurrence network indicates that DfS education research is evolving into a multidisciplinary and technology-driven field that integrates safety management, digital innovation, sustainability, and educational transformation.

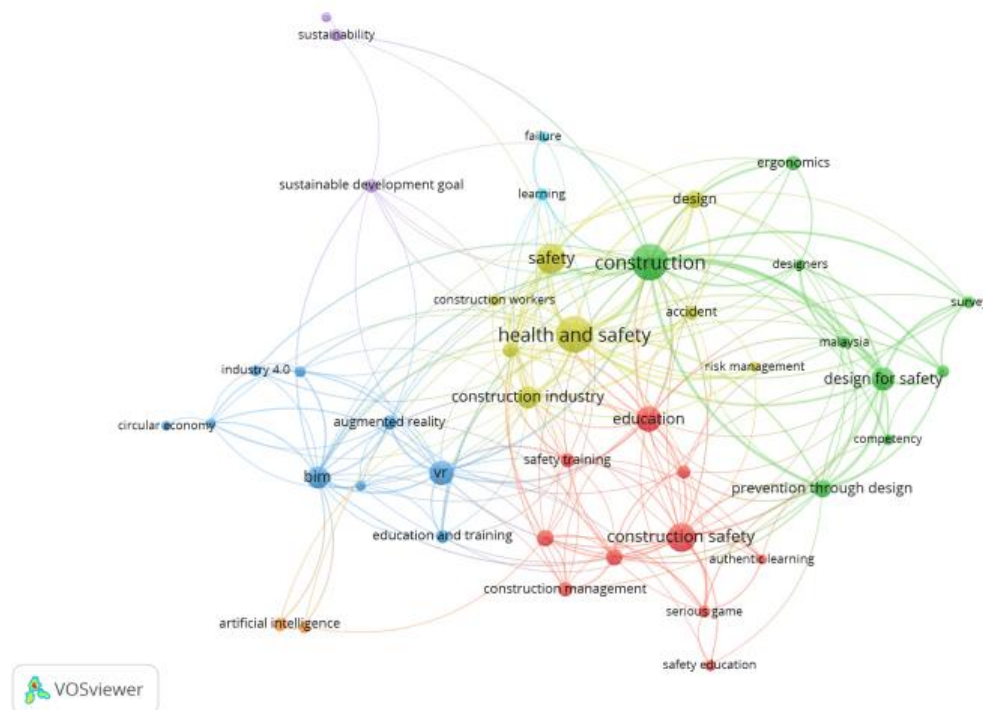


Figure 2: Network Visualization Map of Keywords' Co-Occurrence

RQ4: What Patterns of International Scholarly Collaboration Characterize Design for Safety (Dfs) Research in Education, As Evidenced by Country-Level Co-Authorship Networks?

Figure 3 presents the country-level co-authorship network generated using VOSviewer, highlighting the global research collaboration patterns in the field of Dfs in education. The results indicate that the United States dominates the research landscape, with the highest number of publications (233), citations (2,797), and total link strength (16), signifying its central role in international scholarly collaboration and knowledge production. The strong research performance of the United States may be attributed to its advanced construction industry, substantial research funding, and longstanding emphasis on occupational safety, engineering education, and technological innovation. Similarly, the United Kingdom demonstrated considerable research influence, with 81 publications and 1,274 citations, yielding a total link strength of 9, reflecting strong international research connectivity and high-impact scholarly contributions. These findings suggest that developed countries with mature research ecosystems and established safety regulations tend to lead in advancing Dfs-related educational research. Although China ranked third in publication output (72 documents), its relatively low total link strength suggests limited international collaboration compared to Western countries. This pattern may imply that Chinese research activities are more domestically concentrated despite their increasing research productivity. The significant citation performance of countries such as Australia, Germany, Denmark, and Hong Kong further indicates that impactful Dfs research is strongly associated with nations emphasizing technological integration, digital construction systems, and proactive safety management frameworks.

In addition, the growing participation of emerging and developing economies in DfS education research is particularly evident in Malaysia, South Africa, Nigeria, Ghana, and Saudi Arabia. Malaysia, for example, recorded 32 publications with a total link strength of 3, indicating an active role in collaborative research despite its relatively moderate publication volume. This growing research involvement may be linked to increasing national emphasis on construction safety, higher education reforms, and the adoption of Industry 4.0 technologies within the built environment sector. The presence of African countries such as South Africa, Nigeria, and Ghana demonstrates expanding global awareness regarding occupational safety challenges and the need for safety-oriented educational frameworks in developing economies. However, many countries exhibited low or zero total link strength values, suggesting that international collaboration within the field remains uneven and concentrated among a limited number of research-intensive nations. This imbalance may result from disparities in research funding, institutional networks, technological capacity, and access to international academic collaborations. Furthermore, countries with relatively high citation counts, however, limited collaboration strength, such as South Korea and Hong Kong, suggest that impactful research can still emerge from localized or institutionally concentrated efforts. Overall, the co-authorship network illustrates that DfS education research is increasingly globalized. Nonetheless, scholarly influence and collaborative connectivity remain dominated by a small group of developed countries with strong research infrastructures and established safety cultures.

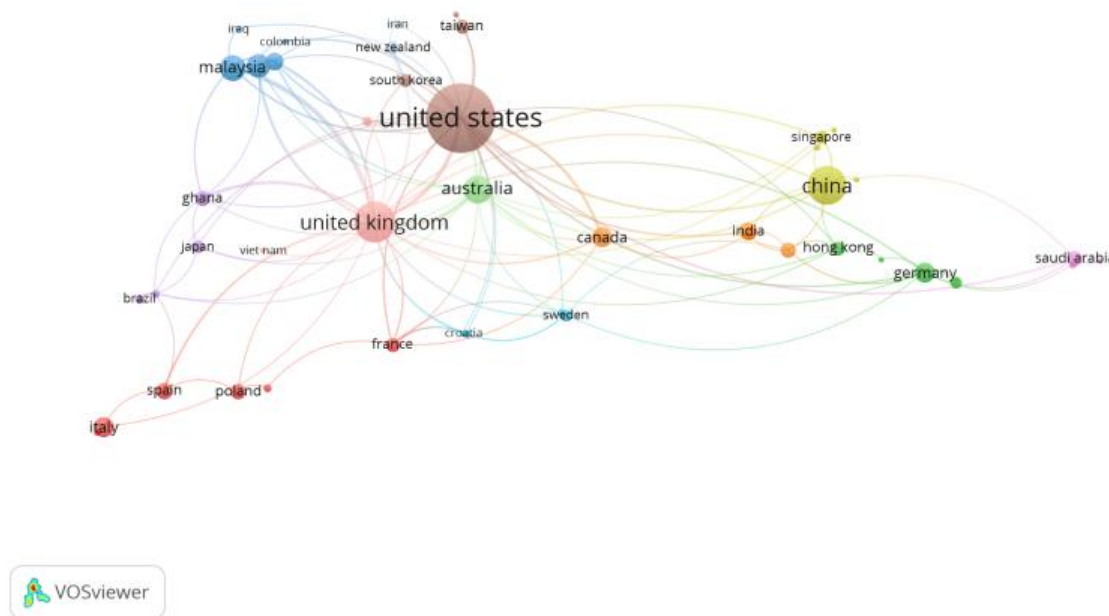


Figure 3: Network Visualization Map of Countries' Co-Authorship

Conclusion

This study examined the intellectual development and research evolution of DfS in education for construction through a comprehensive bibliometric analysis of publications in the Scopus

database from 1939 to May 2026. The analysis addressed four principal research questions concerning publication growth trends, influential scholarly contributions, prevailing and emerging research themes, and international collaboration patterns within the field. By applying bibliometric techniques through Scopus Analyzer, OpenRefine, and VOSviewer, the study provided a systematic overview of the structural characteristics and knowledge development trajectory of DfS research in educational contexts related to construction and engineering disciplines.

The findings indicate a substantial increase in research productivity, particularly after 2014, demonstrating the growing academic and industrial recognition of proactive safety integration within construction education. Earlier studies were relatively limited and fragmented, whereas recent years have seen accelerated publication growth driven by the expansion of digital technologies, Industry 4.0 applications, sustainability initiatives, and heightened awareness of occupational safety responsibilities in the built environment sector. Citation analysis further revealed that highly influential publications are strongly associated with technology-enhanced safety management approaches, including BIM, virtual reality, RFID systems, and automated hazard detection technologies. At the same time, foundational studies on safety culture, worker behavior, and educational interventions continue to exert strong scholarly influence, indicating that contemporary DfS research is built on both technological innovation and established safety management principles.

Keyword co-occurrence analysis revealed that the research landscape is increasingly multidisciplinary, integrating themes in construction safety, engineering education, sustainability, digital transformation, and competency-based learning. The emergence of keywords related to augmented reality, artificial intelligence, digital twin technologies, and machine learning suggests that the field is shifting toward immersive, intelligent learning environments for safety education and training. In addition, country-level co-authorship analysis showed that research productivity and collaborative influence remain largely concentrated within developed countries, particularly the United States and the United Kingdom, due to stronger research infrastructures, technological capabilities, and established safety regulations. Nevertheless, increasing contributions from emerging economies such as Malaysia, South Africa, and Saudi Arabia demonstrate expanding global interest in DfS education and indicate the growing relevance of safety-oriented educational frameworks across diverse regional contexts.

This study contributes to the existing body of knowledge by providing a comprehensive mapping of the intellectual structure, thematic development, and collaborative patterns within DfS education research for construction. The findings offer valuable implications for higher education institutions, policymakers, accreditation agencies, and industry practitioners seeking to strengthen safety-oriented competencies within engineering and construction curricula. The increasing integration of digital technologies into safety education suggests the need for a curriculum that aligns with evolving industrial practices and technological advancements. Furthermore, the findings support the importance of embedding proactive safety principles throughout educational programs rather than treating safety solely as a supplementary or compliance-oriented topic.

Correspondingly, several limitations should also be acknowledged. Note that the analysis relied exclusively on the Scopus database. It included only English-language publications indexed in selected subject areas, potentially excluding relevant studies published in other databases or

languages. In addition, the bibliometric approach primarily focuses on quantitative publication patterns and network relationships, which may not fully capture the qualitative depth and contextual complexity of individual studies. Future research may expand the dataset by incorporating multiple databases, comparative regional analyses, and longitudinal qualitative assessments to obtain a more comprehensive understanding of DfS educational implementation and effectiveness. Additional investigations into emerging technologies, interdisciplinary pedagogies, and industry-academic partnerships may also provide further insights into the future direction of DfS education.

In conclusion, the present bibliometric analysis demonstrates that DfS in education for construction has evolved into a rapidly expanding and increasingly interdisciplinary research field driven by technological innovation, sustainability imperatives, and global occupational safety concerns. The study highlights the critical role of bibliometric analysis in identifying intellectual trends, influential contributions, and collaborative structures within the field. Continued scholarly exploration and stronger international collaboration are essential to further integrate proactive safety principles into construction education and to support the development of future professionals capable of addressing complex safety challenges in modern built environment practices.

Acknowledgments: The authors would like to express their sincere gratitude to Universiti Teknologi Malaysia for providing the necessary resources and support throughout this research. Special appreciation is extended to colleagues and peers who contributed valuable insights and constructive feedback, which greatly enhanced the quality of this paper.

Funding Statement: No Funding

Conflict of Interest Statement: The authors declare that there is no conflict of interest regarding the publication of this paper. All authors have contributed to this work and approved the final version of the manuscript for submission to the the International Journal of Innovation and Industrial Revolution (IJIREV).

Ethics Statement: This study did not involve any human participants, animals, or sensitive data requiring ethical approval. The authors confirm that the research was conducted in accordance with accepted academic integrity and ethical publishing standards.

Author Contribution Statement: All authors contributed significantly to the development of this manuscript. Fuziah binti Ismail and Tantish binti Kamaruddin were responsible for the conceptualization, methodology, and overall supervision of the study. Norhazren Izatie binti Mohd and Hamizah Liyana binti Tajul Ariffin handled data collection, analysis, and interpretation of results. Nurshikin binti Mohamad Shukery, Siti Nurhuda binti Abdul Wahid and Renugala M Shollunayagam contributed to the literature review, drafting, and critical revision of the manuscript. All authors read and approved the final version of the manuscript prior to submission.

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