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The landscape of safety management systems research: A scientometric analysis

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A R T I C L E I N F O

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A B S T R A C T

Safety management systems (SMSs) are widely applied across many industrial sectors, and a large body of literature has been published addressing their design, implementation, effectiveness, and associated challenges. This article presents a high-level analysis of the SMS research domain, guided by a set of questions addressing the contents, structure, and evolution the research domain, its dominant themes and focus topics, the key scientific domains and journals contributing to its development, and the key publications serving as an intellectual basis for SMS related research. The results show a rapidly increasing volume of research outputs and a shift from research based in North America and Europe to Asia and Australia. There is only a limited number of institutions enduringly contributing to the field, and there are relatively few stable research collaborations, with the number of Chinese institutions publishing SMS related research fast expanding in recent years. The domain is strongly interdisciplinary and embedded in applied domains of science, with industrial engineering the most contributing category, as well as categories focusing on the industrial application domains. A temporal evolution of the research activity in different application domains is apparent, with an initial focus on occupational health and safety, followed by process safety, patient safety, food safety, and construction safety. SMS research has a strong relation to safety culture and safety climate research, and while safety and risk management concepts and theories form an important knowledge base for most application domains, the dominant views on accident causation differ between these. Research on SMS in the food industry is relatively separated from the other application domains. Based on the findings, various future research directions are discussed.

1. Introduction

A Safety Management System (SMS) is an organizational tool to develop, plan, measure, analyze, and control the overall safety performance of an organization, and to guide decision-making for selecting safety assurance activities [1]. Various industrial sectors have adopted SMS as a vehicle to improve occupational safety and reduce major accident risks, for instance the process [2], construction [3], and transport industries [4,5]. On the one hand, an SMS must meet the requirements of applicable safety regulations for compliance and certification purposes [6], while on the other hand accounting for the specific hazard profile of the organization and the accident causation patterns [7]. Given the differences in the specific regulatory requirements of various industries, adherence to different safety concepts and theories of accident causation, and the variety of applied tools and techniques, SMSs come in many shapes and forms [8].

Safety management systems can be seen as a business management approach to safety, which has been argued to be an important aspect of bringing safety to the foreground in executive decision-making [9]. However, the increased bureaucratization their implementation entails may also have negative consequences such as reduced marginal yield of safety initiatives and stifling of organizational freedom and innovation [10]. Careful consideration of the role of uncertainty in balancing stability, flexibility, accountability, and control, may therefore be conducive to enhancing safety management [11]. Furthermore, even though there is some evidence that SMS implementation has a positive influence on organizational safety performance [12,13], various challenges and barriers exist in their practical implementation [14,15,16].

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It is clear that SMSs are found in many industrial sectors, serving an integrating function of various safety practices and activities. They extend to various work environments, often multiple departments within an organization, and through auditing mechanisms to external actors such as regulatory bodies and inspectorates. Considering further the multitude of safety-related concepts, theories, and tools on which they build, and similarities SMSs have to other organizational management systems, for instance, related to quality, it is not surprising that a large body of academic work has been published on this topic. Consequently, various review articles have been published addressing specific aspects of this literature. For instance, Robson et al. [12] provide a systematic review of the effectiveness of SMS interventions, Jacxsens et al. [17] review tools for performance assessment and improvement of food SMS, while Couto da Silva and Amaral [18] review success factors and barriers to implementing SMS. Li and Guldenmund [8] provide a broad overview of SMS, addressing their definition, evolution, models, purpose, and common elements. Finally, Swuste et al. [20,97] present comprehensive overviews of the development and context of process and occupational safety management systems, focusing on the development of this domain in terms of the adopted models, theories, and management approaches.

Notwithstanding the value of these systematic narrative reviews, the elaborate volume of research on SMSs makes it very hard to obtain a comprehensive grasp on the overall structure and development of this domain of research, on the knowledge sources and key contributions which have shaped the field, or on the prevalent narrative themes and trends in focus topics. Scientometric methods and techniques present a suitable approach to obtaining such high-level insights into a research domain. By applying mathematical operations on quantitative metrics and citation-related information about scientific documents associated with a domain of knowledge, patterns, developments and trends can be analyzed. By subsequently visualizing and interpreting these using dedicated tools for graphically representing this quantitative information, insights into the research domain can be obtained [21]. Several scientometric analyzes have been published focusing on safety concepts, methods, or application subdomains within the safety sciences, including safety culture [22], safety leadership [23], road safety [24], resilient health care [25], risk perception [26] process safety [27] and process safety in China [28], domino effects [29], construction safety [30], occupational health and safety management [31], and maritime decision support systems for accident prevention [32].

In light of this, the aim of this article is to present a scientometric mapping analysis of the academic research on safety management systems. The overall aim is to obtain high-level insights into how this important domain of safety science has developed, who and what has contributed to this, and what structural and temporal patterns can be identified. The specific research questions are as follows: (i) what are the overall publication trends in regards publication outputs; (ii) what collaborations between countries/regions and organizations exist, and how do these evolve; (iii) what scientific domains are strongly represented and what journals contribute to the development of this research domain; (iv) what are the dominant narrative clusters and how do the focus topics within these evolve over time; and (v) what are the dominant knowledge clusters constituting the intellectual basis of this domain, and what are the key publications within these?

The remainder of this article is organized as follows. In Section 2, the data retrieval process and resulting dataset are described, followed by a brief overview of the applied scientometric techniques and tools to answer the above research questions. The results are shown and interpreted in Section 3. A further discussion is given in Section 4, contextualizing the work and providing directions for future research Section 5. concludes.

2. Data and methods

In scientometric analysis, once research questions are defined, a dataset needs to be determined to serve as a basis for analysis. The process retrieval process is described in Section 2.1, and a brief summary of the obtained dataset is provided. In addition, suitable scientometric techniques and tools are required to detect and visualize the scientometric patterns, which are outlined in Section 2.2. The final step of a scientometric analysis is the interpretation of the resulting graphs and maps, which is provided in Section 3.

2.1. Data retrieval process and resulting dataset

In this study, Web of Science Core Collections (WoSCC), the world's largest and most comprehensive database of scientific publications, is applied. Compared to other databases such as Scopus or Google Scholar, it has a high data quality [21], making it suitable for the current purposes. The following search strategy was applied on 25 April 2020:

Data sources:	Science Citation Index Expanded (SCI-EXPANDED) Social Sciences Citation Index (SSCI)
Timespan:	All years included in the databases: 1900 until 15.04.2020
Retrieved content:	Full records and cited references
Search strategy:	TS = ("safety management system*" OR ("safety management" AND system*))

A topic search (TS) strategy is adopted, which means that the title, abstract, keywords, and keywords plus of the documents included in the WoSCC are searched for combinations of the search terms. Once this list of documents is retrieved, the abstracts are inspected, and only the articles which indeed focus on an aspect of safety management systems are retained. This results in 2283 identified records meeting the criteria, so this search strategy enables to obtain a wide sample of articles addressing various aspects of safety management systems, in line with the research objectives stated in Section 1. The full bibliographic records of these articles are retrieved, including the cited references of these articles.

Table 1 contains a number of key descriptors of the resulting dataset, which are derived using the R package Bibliometrix [33]. The dataset contains 2283 documents, which can be considered the core scientific body of literature on safety management systems. Research contributions to SMSs span the period from 1979 to 2020 (up to 15 April, when the last database update was made before the search was performed), with 708 publication outlets contributing to the literature. Journal articles are the dominant document type by far, with conference and review articles also constituting a significant share. It should be noted that the 'other' category only concerns documents included in the above mentioned WoSCC databases, and include letters, notes and errata. Books are not included in this dataset. With 6048 authors contributing to this domain, it is evident that many researchers have interest in SMS. However, the high collaboration index (2.96) and the low number of average documents per author (0.377) indicate that many authors can be considered more peripheral in this research domain, contributing only to a limited extent to its development. The 300 authors of single-authored documents are likely more indicative of the number of scholars with a more enduring research interest in this topic. With an average number of citations per document of 14.24, the research on SMS can be considered to be rather impactful in the safety research community.

2.2. Applied scientometric methods and tools

Scientometric analysis methods implement mathematical functions to detect patterns, clusters, and trends in textual and meta-information about academic publications. By visualizing derived quantitative metrics representing informational aspects of a research domain, insights can be obtained into its scope, contents, structure, and development. Various scientometric analysis methods and visualization tools have been developed, e.g., Li et al. [66] and Moral-Muñoz et al. [34] for an overview of key concepts, methods, and tools.

An overview of the scientometric analysis and visualization techniques and tools applied in this study to answer the research questions

Table 1
Key characteristics of the analyzed dataset on safety management systems.

Characteristic	Value	Characteristic	Value
Period	1979–2020†	Authors	6048
Sources (journals, books, etc.)	708	Author appearances	7873
Documents	2283	Authors of single-authored documents	300
Journal articles	1916	Authors of multi-authored documents	5748
Conference articles	167	Single-authored documents	334
Review articles	166	Avg. number of documents per author	0.377
Editorials	17	Avg. number of authors per document	2.65
Other (letter, note, etc.)	17	Collaboration index	2.96
Author's keywords	5977	Avg. citations per document	14.24

Note:.
† Documents included up to 15 April 2020.

Table 2
Summary of applied scientometric techniques and tools applied in this study.

ID	Research question focus	Scientometric techniques and tools	Ref.
i	Publication output trends	Regression analysis	–
		Publication analysis (Bibliometrix)	[33]
ii	Collaboration patterns	Visualization of similarities (VOSviewer)	[35]
iii	Scientific categories	Visualization of similarities (VOSviewer)	[35]
		Global science map overlay	[36]
	Journals knowledge flow	Journal distribution analysis (CiteSpace)	[37]
		Journals dual-map overlay	[38]
iv	Narrative clusters and topics	Visualization of similarities (VOSviewer)	[35]
v	Knowledge clusters	Visualization of similarities (VOSviewer)	[35]

listed in Section 1 is given in Table 2. Trends in publication outputs are based on basic scientometric indicators providing summary insights into the studied dataset associated with the domain of research. These summary insights are obtained using the R package Bibliometrix [33], and are shown in Section 2.1 as part of the dataset description. In addition, a simple count of the number of publications per year is made, augmented with regression analysis to estimate the trend type. These results are given in Section 3.1.

Geographical collaboration patterns are identified using the visualization of similarities technique, as implemented in the VOSviewer software [35]. This technique is based on a quantitative analysis of the similarities between documents with respect to a chosen characteristic of the documents; in the present analysis, the country/region and the institution with which the document is associated. Documents are represented as linked nodes in a clustered network, providing insights into the collaboration patterns and relative importance of contributors. A visual overlay of the nodes with additional information about the documents can provide further insights into the domain's developments. In this study, the average publication year of documents associated with a country/region or institution is used as a visual metric to obtain insights into the temporal developments in the collaboration networks. The results of these analyzes are shown in Section 3.2.

Patterns in the scientific categories with which SMS research has been associated are identified by mapping the scientific categories on the global science map by Carley et al. [36], using the VOSviewer software [35]. This map provides a very high-level overview of all scientific disciplines, which is clustered in major thematic areas to facilitate interpretation. Mapping the journal categories of SMS related research on this map provides insights into what scientific domains actively contribute to the development of this research area, which is presented in Section 3.3.

The information flow between journals provides insights into how specific domains of research (citing articles) are influenced by other domains (cited articles). This aids understanding of what scientific communities and academic fields contribute to the development of the field and helps unravel the dominant patterns in the use of academic knowledge. It also facilitates the identification of the main journals supporting the domain's development, which can be considered the main knowledge carriers. The analysis is performed with CiteSpace software [37], utilizing the journal dual-overlay map by Chen and Leydesdorff [38], with the results shown in Section 3.3.

The visualization of similarities technique, as implemented in the VOSviewer software [35], is applied to construct narrative clusters from the author keywords provided in the documents in the SMS dataset described in Table 1. Such narrative clusters provide high-level insights into the scope and structure of the research domain, especially in what topics are related to each other within the research domain, and what topics are in focus. An overlay of the average publication year in which the keywords appeared provides further insights into the temporal developments of the thematic narrative clusters, which is useful to detect trends in the prevalent focus topics over time. These results are described in Section 3.4.

Knowledge clusters in the SMS literature are identified and visualized using co-citation analysis, as implemented in the VOSviewer software [35]. Co-citation analysis was introduced by Small [39] to detect the strength of relationship between articles. Documents are co-cited when they appear together in another document's reference list. If such co-citations occur frequently, this can be taken as an indication that these documents are in some way related to one another. Aggregating co-citation links between frequently cited documents within a research domain and clustering these provide insights into documents that form knowledge clusters driving the developments within the studied domain. These frequently co-cited clusters can be considered as the intellectual basis of this domain, in which the most frequent documents are its key drivers for knowledge development [40]. Results are shown in Section 3.5.

3. Results

3.1. Trends in research outputs

Fig. 1 depicts the annual trend of the number of publications in the SMS research domain, as obtained in the dataset of Section 2.1. The global trend shows that an exponential growth function approximates the volume of literature on SMS well. After a few early contributions at the end of the 1970s and early 1980s, and an approximate 10 year

Table 3
Top 10 highly productive countries/regions in safety management system research.

Countries/Regions	NP	TC	AC	APY	Degree	Cluster
China	390	4156	10.66	2016.20	24	red
United States of America	363	5559	15.31	2012.25	28	red
United Kingdom	254	5516	21.72	2011.53	31	green
the Netherlands	146	3103	21.25	2012.46	25	blue
Australia	128	2482	19.39	2014.54	21	australia
South Korea	116	989	8.53	2014.78	9	red
Italy	103	2357	22.88	2012.59	24	green
Canada	101	1699	16.82	2013.08	26	red
Spain	90	2092	23.24	2013.57	20	blue
Belgium	72	1836	25.50	2013.83	27	blue
Japan	72	657	9.13	2010.61	12	red

Notes: Degree = Number of links of a node | NP = number of publications | TC = total citations | APY = average publication year | AC = average citations | Cluster = collaboration cluster in Fig. 2.

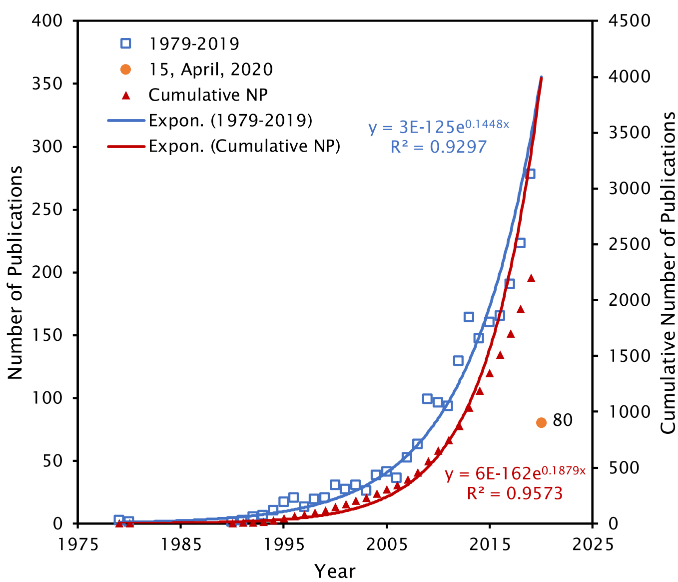

Fig. 1. Research trends of safety management system research.

period in which no new publications were made, the SMS field started to see a steady output in scholarly activity from the early 1990s onwards, with an average publication rate of around 20 articles per year. From around the early 2000s onwards, a dramatic increase in research output volume can be identified, from around 30 articles annually published in the early 2000s to well over 200 in recent years. The very first contributions to safety management systems concern a two-part article by Ayoub M.A. published in *Journal of Occupational Accidents* (the forerunner of *Safety Science*), who describes the design of an information system to record accident and safety records [41], and an optimization approach to develop optimal inspection plans [42]. This original idea of developing a bureaucratic system of keeping safety-related records for directing the allocation of scarce organizational resources is at the core of the business function served by a safety management system as described e.g., by Mauriño [9]. Nevertheless, judging by the very low number of citations these articles by Ayoub have attracted (2 and 0, respectively), the academic roots of SMS for industrial safety are not widely known.

3.2. Geographical collaboration patterns

3.2.1. Countries/regions collaboration network

Fig. 2 shows the network of collaboration on SMS related research between countries/regions. Four clusters are identified. The red cluster is the largest and contains the United States of America (USA) and China as key contributing countries, spanning further across North America, East and South Asia, and Oceania. Considering the results of Table 3, other key contributors are Australia, South Korea, Canada, and Japan, with the strongest collaborations observed between USA and China, China and Australia, USA and Canada, and USA and South Korea. The second largest (green) cluster centers around the United Kingdom (UK), which accounts for all significant research collaboration links in this cluster and with other clusters. It extends further to central, eastern, and southern European areas, with Italy, France, and Germany other significant contributors. The Netherlands is at the center of the third largest (blue) cluster, which further contains Belgium and Spain as important contributors as seen in Table 3. The strongest collaboration links exist between the Netherlands and Belgium, the Netherlands and the UK, and to a lesser degree, the Netherlands and the USA. The smallest (yellow) cluster, which has relatively weak collaboration links, contains the Nordic countries Sweden, Finland, and Norway as the most significant contributors, with Iran and Turkey being additional countries grouped in this cluster.

The temporal evolution of the active countries in SMS related research can be seen in Fig. 3, where the node colours correspond to the average publication year of its associated documents. Referring also to Table 3, it is seen that within the largest (North American – Australasian) cluster, Japan, the USA, and Canada have temporally more distant publication years. This indicates that these countries were influential at earlier development stages of the SMS research domain but have been comparatively less active in recent years. In contrast, Australia, South Korea, and especially China have become very active in recent years, with China having become the largest contributor to SMS research as seen in Table 3. The second largest cluster, with the UK as its figurehead, has contributed significantly in earlier periods of the research domain, but is comparatively less active recently. In the third cluster, it is seen that the Netherlands has been highly influential earlier on, with Spain and Belgium being more recently active countries. In the fourth cluster, Finland and Iran are the most recently active countries.

From Table 3, some additional insights can be obtained. First, the UK is the most connected country in SMS research, followed by the USA, Belgium, Canada, the Netherlands, China, and Italy. These countries can therefore be considered the key drivers of collaborative knowledge creation, as it is known that international collaboration can be instrumental for increased productivity and higher acceptance of research outputs [43,44]. Second, in terms of research impact as measured by the average citation rates of the publications of the countries/regions, it is seen that research contributions from Belgium, Spain and Italy are significantly more impactful, with average citation rates of 25.50, 23.24, and 22.88, respectively, compared to the average document citation rate of 14.24 as found in Section 2.1. Of the top 5 most contributing countries, the UK and the Netherlands have the highest academic impact, with average citation rates of 21.72 and 21.25, respectively.

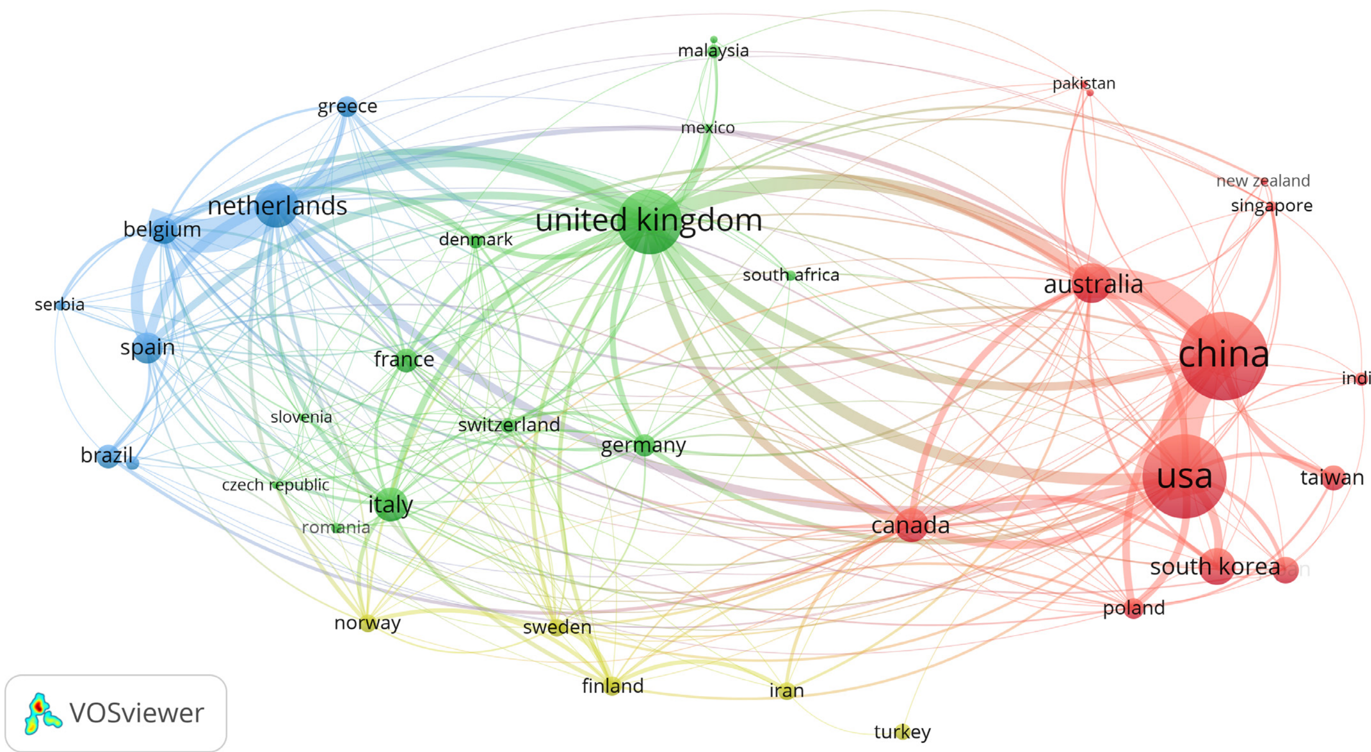

Fig. 2. Countries/regions collaboration network in safety management system research, Number of publications ≥10, visualized using VOSviewer [35].

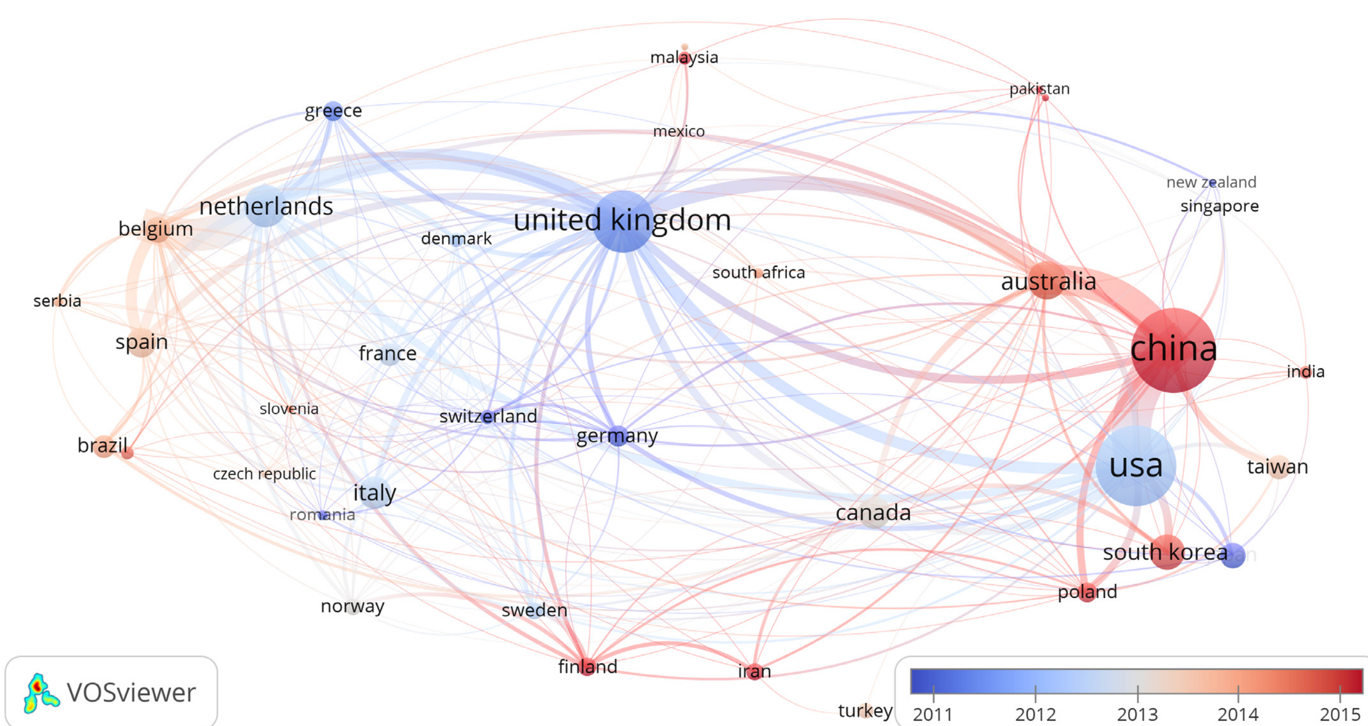

Fig. 3. Average publication year of countries/regions collaboration network in safety management system research, number of publications ≥10, visualized using VOSviewer [35].

3.2.2. Institutions collaboration network

Fig. 4 shows the collaboration network of institutions, where the colours indicate clusters of collaborating institutions Fig. 5. shows the same network with a color overlay corresponding to the average year of publications originating from these organizations, to indicate the temporal evolution of institutional activity and collaborations Table 4. provides further details and additional information about the top 10 most productive institutions in the SMS research domain.

While Fig. 4 distinguishes nine collaboration clusters, it is seen that there are relatively few institutions that consistently work together on SMS research. Notable collaborations can be identified in the blue cluster between Huazhong University of Science and Technology (China)

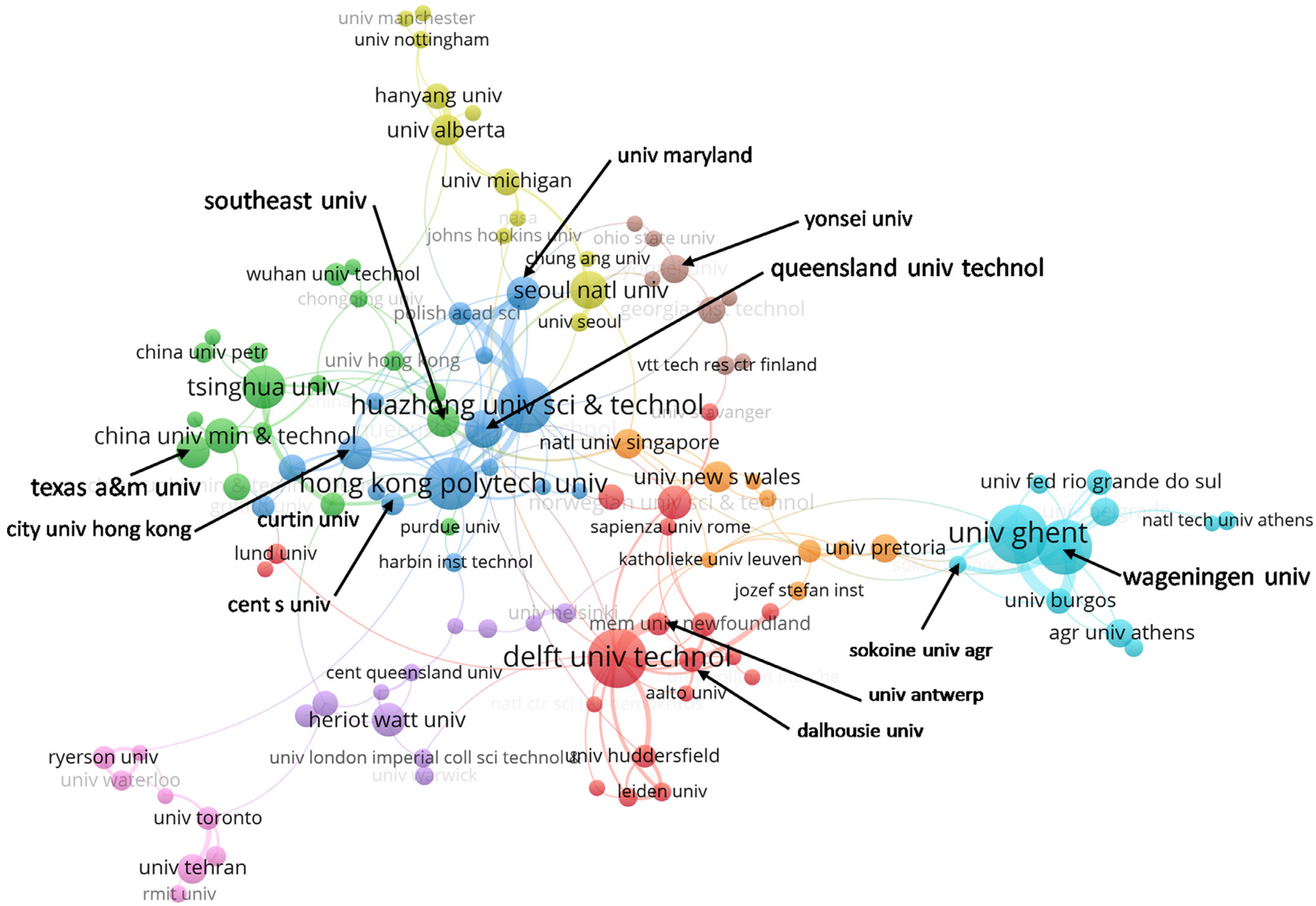

Fig. 4. Institutions collaboration network in safety management system research, Number of publications $\geq$5, visualized using VOSviewer [35].

Table 4
Top 10 highly productive institutions in safety management system research.

Institution	NP	TC	AC	APY	Degree	Cluster
Ghent University	45	1131	25.13	2013.87	10	light blue
Delft University of Technology	44	879	19.98	2013.61	18	red
Huazhong University of Science and Technology	39	651	16.69	2016.74	13	blue
Wageningen University	39	1039	26.64	2013.51	9	light blue
Hong Kong Polytechnic University	36	655	18.19	2013.36	15	blue
Tsinghua University	26	451	17.35	2015.60	9	green
Queensland University of Technology	21	325	15.48	2016.05	12	blue
Seoul National University	21	339	16.14	2015.19	6	yellow
China University of Mining and Technology	19	59	3.11	2016.94	6	green
City University of Hong Kong	18	289	16.06	2013.71	10	blue
Heriot-Watt University	18	218	12.11	2010.06	4	purple
Norwegian University of Science and Technology	18	213	11.83	2013.67	9	red
Texas A&M University	18	206	11.44	2013.82	1	green

Notes: Degree = Number of links of a node | NP = number of publications | TC = total citations | APY = average publication year | AC = average citations | Cluster = collaboration cluster in Fig. 4.

on the one hand, and Hong Kong Polytechnic University (China), Polish Academy of Science (Poland), and the University of Maryland (USA) on the other. A strong collaboration exists as well between Hong Kong Polytechnic University (China) and Queensland University of Technology (Australia) in the cluster. In the red cluster, which is dominated by Delft University of Technology (Netherlands), significant collaborations exist between this organization on the one hand, and Antwerp University (Belgium), Dalhousie University (Canada), University of Huddersfield (UK), and Leiden University (Netherlands). A very strong collaboration is identified between Ghent University (Belgium) and Wageningen University (Netherlands) in the cyan cluster, with both having close collaboration links with University of Burgos (Spain) and Sokoine University of Agriculture (Tanzania) as well. Finally, in the green cluster, a well-developed collaboration between Tsinghua University (China) and Curtis University (USA) is found. While clearly there are many more collaboration links within and across clusters, those appear to be less regular.

Considering the temporal evolution of the research collaborations on SMS as shown in Fig. 5 and Table 4, it appears that the research cluster with Ghent University (Belgium) and Wageningen University (Nether-

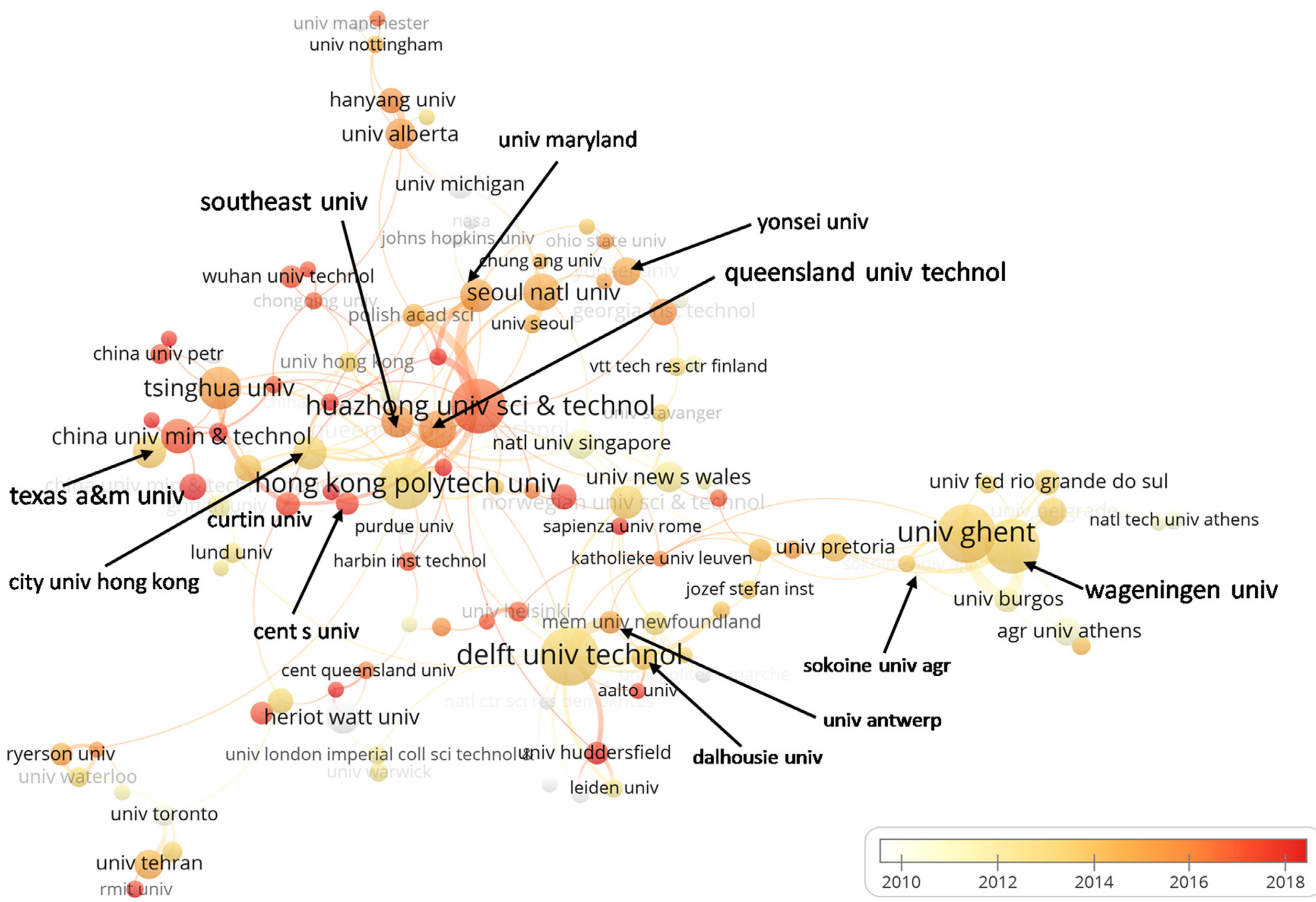

Fig. 5. Average publication year of each institution collaboration network in safety management system research, number of publications ≥5, visualized using VOSviewer [35].

lands) at its core is a longstanding and steadily active collaboration network, with an average year of publication around 2013.5. These two organizations have relatively extensive but stable collaboration partners, with 10 and 9 institutional links, respectively. The cluster around Delft University of Technology (Netherlands) shows a somewhat different picture: while this core institution has been steadily active with an average publication year of 2013.6, it has more collaboration links (18) which are more dynamic over time. For instance, collaborations with Leiden University (Netherlands), Dalhousie University (Canada), and Memorial University of Newfoundland (Canada) are on average more temporally distant, while collaborations with Antwerp University (Belgium), KU Leuven (Belgium), Aalto University (Finland), and University of Huddersfield (UK) are more recent. In Asia, there are several highly productive institutions that have been active in SMS research for a long time, for instance Hong Kong Polytechnic University (China) and City University of Hong Kong (China), having average publication years of 2013.4 and 2013.7. However, the institutional picture here displays a high degree of dynamism, with many institutions becoming active in SMS research in more recent years. These include, for instance, National University of Singapore, Seoul National University (South Korea), Yonsei University (South Korea) and Tsinghua University (China) as relatively early adopters. Huazhong University of Science (China) and Technology and China University of Mining and Technology have very rapidly become highly productive institutions despite their very recent average years of publication (2016.7 and 2016.9, respectively), and many more institutions have recently become active in this domain, for instance China University of Petroleum, Harbin University (China) and Wuhan University of Technology (China). Referring to Fig. 3, the recent research activity on SMS in Australia is due to highly active institutions such as Queensland University of Technology and Central Queensland University, with Griffith University an early driver of SMS related research in Australia.

In terms of research impact as measured by the average citation score of publications, the most impactful and highly productive institutions are Wageningen University (Netherlands) and Ghent University (Belgium), followed by Delft University of Technology (Netherlands) and Hong Kong Polytechnic University (China). Of the most recently active organizations, the publications of which have had less time to accrue citations, Huazhong University of Science and Technology (China), Tsinghua University (China), and Queensland University of Technology (Australia) have comparatively more impactful research contributions.

3.3. Patterns in scientific categories and information flow between journals

3.3.1. Scientific categories

The classification of journals in scientific categories in the WoSCC database serves as a marker of the scientific disciplines and domains on which the articles published in journals are focused. Aggregating the categorizations of the dataset of SMS research obtained in Section 2.1 enables a very high-level view of how SMS research is situated within the body of scientific knowledge included in the datasets obtained from WoSCC as identified in Section 2.1. It also provides insight in the scientific categories with which the research domain is primarily associated. The analysis makes use of the global science map by Carley et al. [36] and is performed using the VOSviewer software [35].

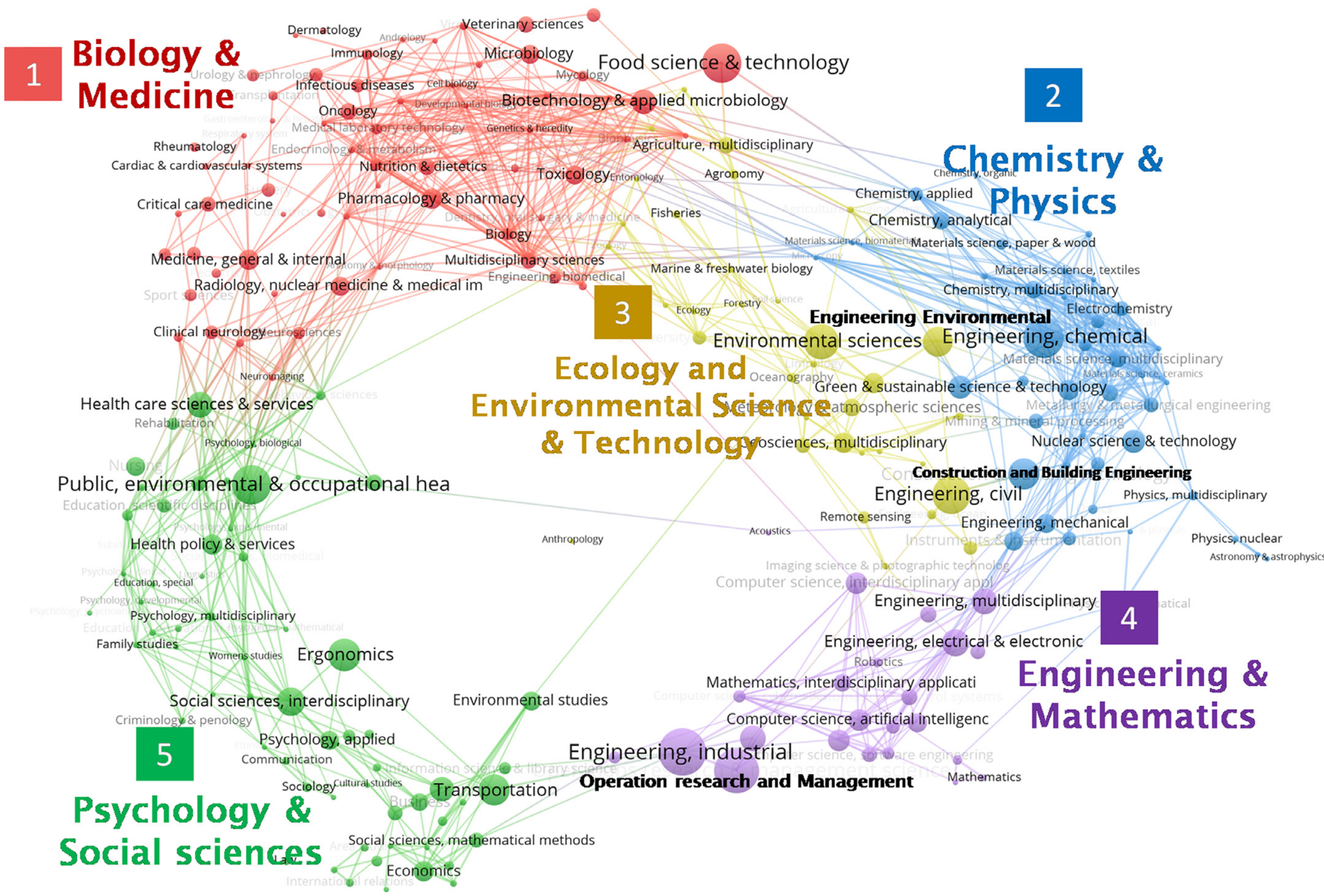

Fig. 6. Scientific categories network of safety management system research on the global science map by Carley et al. [36], visualized using VOSviewer [35].

Table 5
Highly productive scientific categories for safety management system research, categories with at least with 50 papers in the dataset of Section 2.1.

Web of Science Categories	Cluster	NP	APY	AC
Engineering, Industrial	4	456	2013.45	22.12
Operations Research & Management Science	4	367	2013.02	24.71
Engineering, Chemical	2	265	2011.46	10.51
Public, Environmental & Occupational Health	5	255	2012.52	14.16
Food Science & Technology	1	254	2013.30	17.00
Engineering, Civil	3	215	2013.57	14.41
Environmental Sciences	3	167	2011.52	12.58
Ergonomics	5	142	2012.24	20.71
Transportation	5	120	2013.02	22.43
Construction & Building Technology	2	112	2014.61	20.44
Engineering, Environmental	3	95	2010.71	19.61
Social Sciences, Interdisciplinary	5	82	2012.06	28.38
Engineering, Electrical & Electronic	4	68	2013.91	6.99
Engineering, Multidisciplinary	4	62	2011.69	4.84
Transportation Science & Technology	5	60	2011.32	6.30
Health Care Sciences & Services	5	59	2011.97	16.42
Management	5	50	2014.14	12.82

Notes: NP = number of publications | APY = average publication year | AC = average citations | Cluster = high-level clusters on the global science map of Fig. 6.

The results are shown in Fig. 6, which shows five clusters of the global scientific body as proposed by Carley et al. [36]: #1 '*Biology and Medicine*', #2 '*Chemistry and Physics*', #3 '*Ecology and Environmental Science and Technology*', #4 '*Engineering and Mathematics*', and #5 '*Psychology and Social Sciences*' Table 5. provides an overview of the categories represented in the SMS research domain with which 50 or more documents are associated. It also shows the average publication year and the average citation score, giving insights into the temporal dynamics and relative impact of various focus domains within the research field.

The results show that SMS research is highly interdisciplinary, with scientific categories across all five overall scientific clusters contributing to this research domain. The key scientific categories are '*Engineering, Industrial*', and '*Operations Research & Management Science*', indicating that SMS is primarily linked with the improvement of industrial processes and operations. While these scientific categories are mapped within cluster #2 '*Engineering & Mathematics*', these domains are rather closely connected to cluster #5 '*Psychology & Social Sciences*' through a focus on improvement processes and organizational and human factors issues. In this context, it note worthy that the very first scientific contributions to SMS by Ayoub [41,42] originate from an Industrial Engineering department at North Carolina State University (USA). The social science dimension of SMS research is also highlighted by the relatively high contributions of the scientific categories '*Ergonomics*' (#5), '*Management*' (#5), and '*Social Sciences, Interdisciplinary*' (#5).

Furthermore, it is apparent that SMS research is very application-oriented, with several scientific categories associated with various application domains significantly contributing to the research domain. These include, for example, '*Engineering, Chemical*' (Cluster #2), '*Public, Environmental & Occupational Health*' (Cluster #5), '*Food Science & Technology*' (Cluster #1), and '*Engineering, Civil*' (Cluster #3) are in the context of SMS research mostly the context in which applications for SMS design and use are developed and tested. This combination of application domain-specific knowledge and methodological knowledge for designing, implementing, and testing SMSs leads to a highly interdisciplinary research domain. Apart from a visual appreciation of the interdisciplinary nature of SMS research in Fig. 6, where categories across all five major scientific clusters are represented, the Stirling-Rao diversity index provides further confirmation of its interdisciplinarity. This metric calculates the aggregate distance between connected scientific categories, giving more weight to more frequently detected categories and pairs of more distant categories [45]. For the SMS research domain, this index is calculated as 0.808, which is a very high score.

Finally, it is observed from Table 5 that there is some variation in the average publication year of the scientific categories associated with particular application domains. For instance, '*Engineering, Chemical*' (APY = 2011.46) and '*Health Care Sciences & Services*' (2011.97) are more temporally distant than application domains such as '*Engineering, Civil*' (2013.57) and '*Construction & Building Technology*' (2014.61). This suggests that some application domains have adopted SMS later than others, and/or that the research activity focusing on different domains is not equally active across time. Likewise, inspecting the average citation scores in Table 5, it is apparent that the core scientific categories necessary for the conceptualization, development, implementation, and testing of SMS, such as '*Social Sciences, Interdisciplinary*', '*Operations Research & Management Science*', and '*Engineering, Industrial*' are comparatively more impactful that application-focused scientific categories. With respective average citation scores of 28.32, 24.71, and 22.12, these are scientifically more impactful than e.g., '*Engineering, Chemical*' (AC = 10.51), '*Public, Environmental & Occupational Health*' (14.16), '*Engineering, Civil*' (14.41), and '*Food Science & Technology*' (17.00).

3.3.2. Knowledge flow between journal clusters and highly influential journals

Fig. 7 shows the results a dual-map overlay analysis of the SMS research dataset of Section 2.1. The figure uses the journals dual-map developed by Chen and Leydesdorff [38], and maps the journals in which the articles in the dataset are published. The dual-map overlay analysis, performed using CiteSpace [37], then traces the cited journals and connects the journals in both maps. Hence, the analysis aims to detect patterns in the knowledge flow from cited to citing journals, providing high-level insights into what domains of knowledge are used as a basis for creating new SMS research outputs. To facilitate this interpretation, labels are provided on the dual-map overlay, which represent clusters of journals focusing on similar themes. Furthermore, the software constructs ovals on the maps, which represent journal clusters in which a high activity in citing or cited journals is detected within the dataset. The size of these ovals is proportionate to the number of citing publications for the citing journals, and the number of citations received for the cited journals. The upper section of Fig. 7 (part I) shows the citation links between the journals directly, whereas the lower section (part II) further condenses the information by concentrating on the lines linking cited and citing journals. This is done by creating lines with a width proportional to the frequency of citation links between citing and cited domains, using the z-score of the citation links, as explained by Kim et al. [46].

Fig. 7 shows that SMS research is mainly published in the journal clusters '*Veterinary, animal, science*', '*Medicine, medical, clinical*', '*Mathematics, systems, mathematical*', and '*Psychology, education, health*', see also Table 6. The dominant cited journal clusters in this research domain are '*Environmental, toxicology, nutrition*', '*Health, nursing, medicine*', '*Systems, computing, computer*', and '*Psychology, education, social*'. The patterns of the citation links furthermore indicate that it is quite common that knowledge from different cited journal clusters is applied to create new research outputs. For instance, knowledge from '*Systems, computing, computer*' and '*Psychology, education, social*' frequently used together as a basis for advancing SMS research associated with the '*Mathematics, systems, mathematical*' journal cluster. Also the clusters '*Health, nursing, medicine*' and '*Psychology, education, social*' are commonly found together to advance '*Psychology, education, health*' related SMS research.

Table 7 shows the top 20 most productive journals on SMS research, whereas Table 8 shows the top 20 journals in terms of citations received from publications addressing SMS. It is seen that *Safety Science, Food Control, Journal of Loss Prevention in the Process Industries*, and *Accident Analysis and Prevention* appear in the top 5 of both lists. This indicates that these journals can be regarded as the core academic journals within the SMS research field, with *Safety Science* by far the most productive and impactful journal. The average publication year suggests that SMS research in process safety originated comparatively early, with average publication years for *Journal of Loss Prevention in the Process Safety* being 2010.4, for *Process Safety Progress* 2011.7, for *Process Safety and Environmental Protection* 2012.7, and for *Journal of Hazardous Materials* even dating back to 2003.8. Other application domains appear to have become active somewhat later, with for instance food-related SMS being published in *International Journal of Food Microbiology* (APY = 2011.1), *British Food Journal* (APY = 2012.7), *Journal of Food Protection* (APY = 2012.6) and *Food Control* (APY = 2013.8), transport-related SMS published in *Accident Analysis and Prevention* (APY=2013.1) and *Transportation Research Record* (APY = 2015.7), and construction related SMS published in *Automation in Construction* (APY = 2015.2) and Journal of Construction Engineering and Management (APY = 2015.8).

3.4. Narrative clusters and trends in focus topics

Author keywords provide essential insights into the main focus topic of academic publications. A terms co-occurrence analysis of the keywords associated with the safety management research domain is shown in Fig. 8. The co-occurrence analysis and clustering are performed using the VOSviewer software [35], showing what topics are related to each other. This analysis provides insights into the dominant narrative patterns in the research domain, i.e., in the kinds of issues which are addressed in scholarly contributions. An overlay of the average publication year in which terms appeared is shown in Fig. 9, providing additional insights into the evolution of focus topics over time Table 9. lists the most frequently occurring keywords in safety management research per cluster as identified in Fig. 8, along with the average publication year associated with the term.

From Fig. 8, it is seen that there are seven dominant narrative clusters in the research domain. Five of these focus on application domains: process safety, construction safety, patient safety, occupational health and safety, and food safety. The remaining two focus on methods for safety management systems, and on safety culture and safety climate. Referring also to Fig. 9 and Table 9, a number of observations can be made about these clusters. First, considering the weighted average of the keywords by year of publication (WAKY), it is apparent that there is a temporal evolution in the application domains in which safety management systems research is in focus. The research domain experienced a first fo-

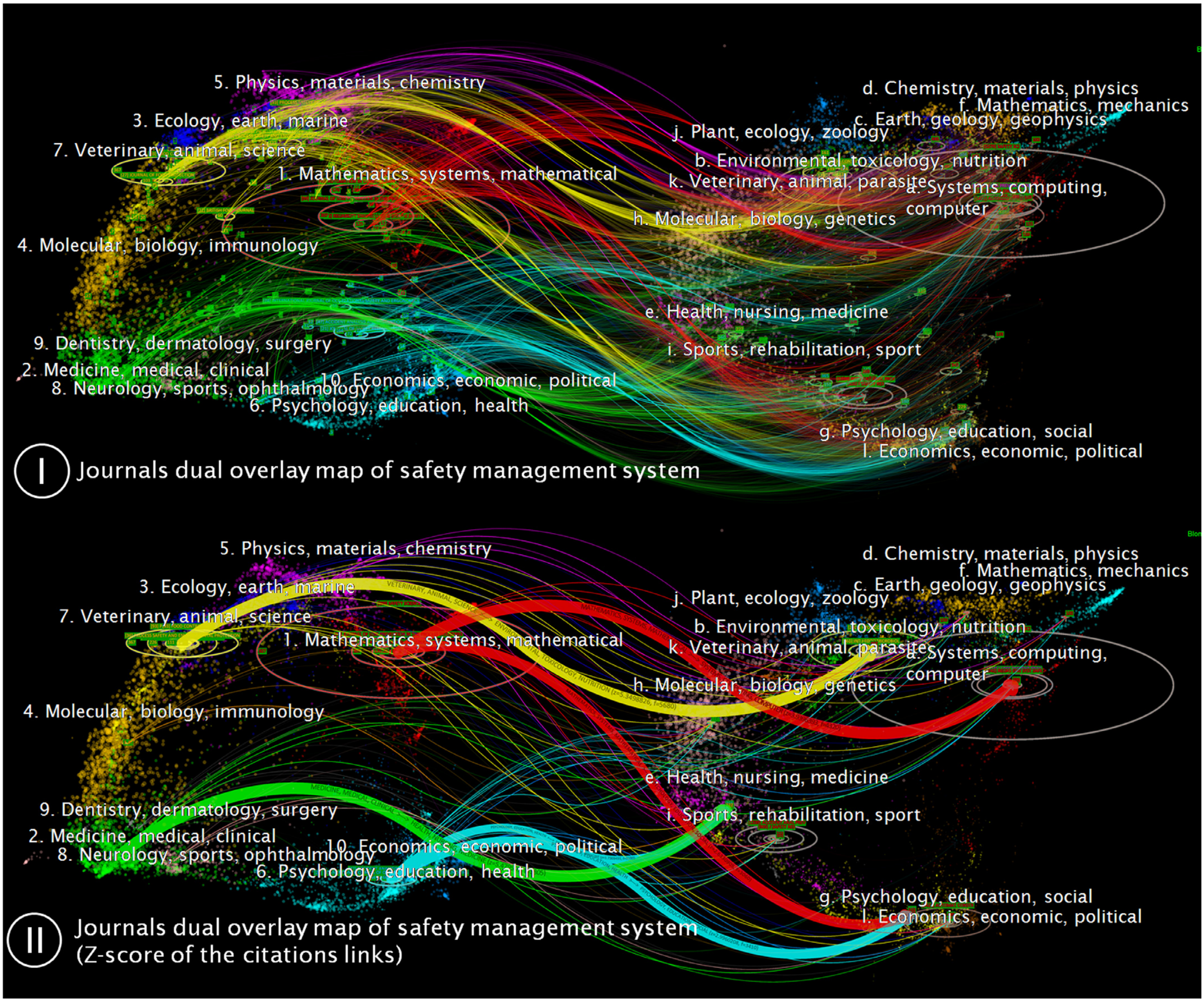

Fig. 7. Journals dual overlay map of safety management systems research, visualized using CiteSpace [37].

Table 6
Citation trajectories of safety management systems research at the level of journal clusters.

No.	Citing domain	Cited domain	z-score	color
1	Veterinary, animal, science	Environmental, toxicology, nutrition	5.35	yellow
2	Medicine, medical, clinical	Health, nursing, medicine	5.48	green
3	Mathematics, systems, mathematical	Systems, computing, computer	2.94	red
	Mathematics, systems, mathematical	Psychology, education, social	2.63	red
4	Psychology, education, health	Health, nursing, medicine	1.73	light blue
	Psychology, education, health	Psychology, education, social	2.99	light blue

Notes: Z-score as calculated in Kim et al [46]. | Colour as in the citation links of Fig. 6.

cus on occupational health and safety applications (WAKY = 2011.6), with important keywords '*health and safety*', '*integrated management system*', '*audit*', '*ohsas 18001*', and '*environmental management*'. This cluster stresses the importance of integrated systems covering health, safety, and environmental aspects of occupational accident and disease prevention. It has a strong link with certification standards and quality management. The bulk of research activity on safety management systems in process and patient contexts occurred largely in the same time period, however with different focus topics. Whereas process safety management (WAKY = 2012.99) initially focused on '*major accidents*', '*accident investigation*', '*near misses*', and '*human error*', more recently there has been attention to '*human factors*' and '*resilience engineering*'. Patient safety management systems research (WAKY = 2012.95) had an initial focus on '*database*' and '*information systems*', '*medical errors*' and '*medication errors*', and '*incident reporting*'. However, more recently topics such as '*socio-technical systems*', '*resilience*', '*resilience engineering*' and '*safety-2*' are in focus. Food safety management research (WAKY = 2013.08) is the second most recent major application cluster. Important keywords here are '*hazard analysis*', '*haccp*' (hazard analysis and critical control points), and '*SMEs*' as early focus topics. With a more recent focus on

Table 7
Top 20 highly productive journals in safety management research.

Citing journal	NP	APY
Safety Science	299	2013.85
Journal of Loss Prevention in the Process Industries	99	2010.35
Food Control	93	2013.84
Process Safety Progress	93	2011.70
Accident Analysis and Prevention	47	2013.06
Automation in Construction	45	2015.22
Reliability Engineering & System Safety	42	2008.86
Process Safety and Environmental Protection	36	2012.69
Journal of Construction Engineering and Management	35	2015.83
Journal of Food Protection	27	2012.56
International Journal of Occupational Safety and Ergonomics	24	2014.83
Journal of Hazardous Materials	24	2003.88
British Food Journal	22	2012.68
Journal of Safety Research	21	2010.71
Journal of Cleaner Production	18	2014.94
Sustainability	18	2018.39
International Journal of Environmental Research and Public Health	17	2018.53
Transportation Research Record	17	2015.65
Cognition Technology & Work	15	2015.40
International Journal of Food Microbiology	14	2011.14

Table 8
Top 20 highly cited journals in safety management research.

Cited journal	NC
Safety Science	5290
Food Control	2006
Automation in Construction	1421
Accident Analysis and Prevention	1342
Journal of Loss Prevention in the Process Industries	1324
Reliability Engineering & System Safety	1141
Journal of Safety Research	906
Journal of Food Protection	710
Journal of Construction Engineering and Management	684
International Journal of Food Microbiology	661
Journal of Construction Engineering and Management	489
Journal of Cleaner Production	457
Journal of Hazard Materials	445
Applied Ergonomics	419
Trends in Food Science and Technology	374
Journal of Applied Psychology	368
Quality and Safety in Health Care	365
Journal of Computing in Civil Engineering	347
Risk Analysis	344
Process Safety Progress	321

'*ISO 22000'*, this cluster also recognizes the importance of industrial certification standards. The most recent research activity in safety management system research concerns the construction safety application area (WAKY = 2015.33). With an early focus on '*accident prevention*' and '*occupational accidents*', important keywords here are behavior-focused, e.g. '*behavior-based safety*', '*safety behavior*', and '*unsafe behavior*'. Other significant keywords are '*data mining*', '*building information modeling*' and '*internet of things*'.

'Food safety culture' and 'food safety climate' are among the most recent keywords in food safety management research. This observation is interesting because the generic cluster safety culture/safety climate, which shows strong links with the occupational health and safety, process safety, and construction safety management research clusters, is actually the oldest (WAKY = 2011.57), taking a central position in the keyword co-occurrence network. This suggests that while application domains focusing on personal and process safety have considered safety management systems already for a long time as contributing to the organizational safety culture, this is only recently the case in the food safety application domain. Finally, the methods-focused cluster is also quite recent (WAKY = 2014.02), and includes classical risk assessment methods as keywords, such as '*fault tree analysis*', '*ahp*' (analytic hierarchy process), '*bayesian network*', '*bowtie*', and '*fuzzy logic*'. The comparatively later focus on methods suggests that research initially focused on generic principles, mechanisms, and frameworks for safety management systems, where more recent research focuses on the applicability or development of safety management systems with specific modeling approaches.

3.5. Intellectual basis of sms research: knowledge clusters and key publications

As outlined in Section 2.2, a co-citation analysis provides insight into the clusters of sources which collectively serve as a knowledge basis for the development of a research domain. The networks of influential articles (as measured through their citation scores) provide insight into the main ideas, concepts, theories, and approaches which drive the production of new knowledge. A clustering of the networks also provides high-level insights into how well integrated the overall domain is, as it can discern subdomains within the overall research domain which remain relatively secluded from knowledge clusters lying at the basis of developments in other subdomains.

The results of this co-citation analysis of the safety management system research domain are shown in Fig. 10, with the top 10 most influential publications listed per cluster in Table 10. It is seen that five

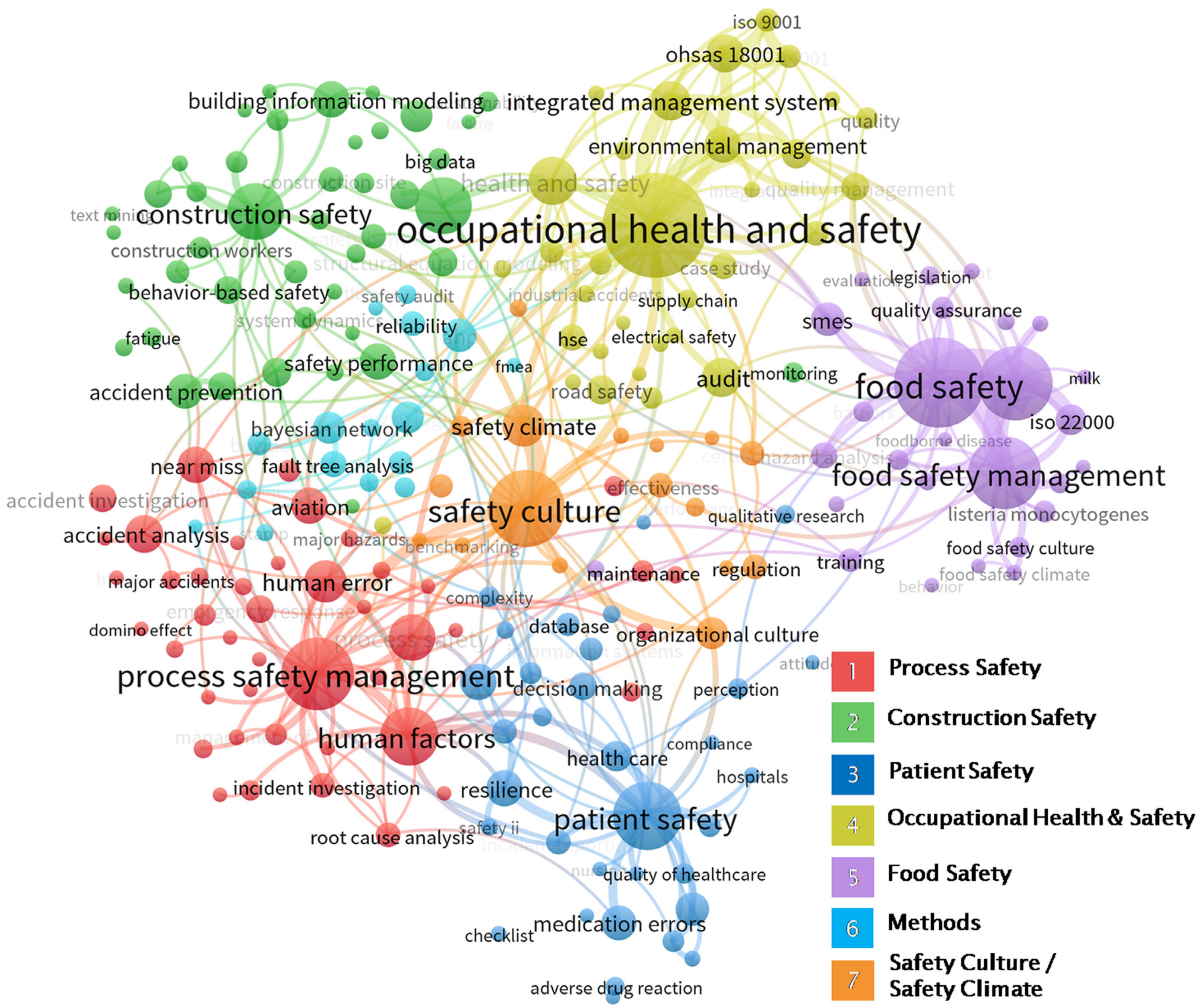

Fig. 8. Keywords clusters in safety management system research based on the co-occurrence connections, keywords which appeared at least 5 times, visualized using VOSviewer [35].

co-citation clusters can be identified: three generic clusters addressing more conceptual and theoretical issues, and two applications-focused clusters concentrating literature on specific industrial sectors in which safety management systems are applied.

The green cluster is labelled '*Risk and safety management concepts and theories*', as it contains several key publications introducing or describing very influential ideas on how safety can be managed or facilitated. It includes very Reason's influential work on human error [47,48], Heinrich's ideas on the accident pyramid and linear accident sequences [49], Perrow's systems-focused work on Normal Accident Theory [50], the multi-level systems-theoretical models focusing on control and feedback by Rasmussen [51,98] and Leveson [52], with resilience engineering [88] as the most recently included conceptual development in safety management research.

The yellow cluster is labelled '*Safety culture and safety climate*'. As key documents, it contains the foundational work by Zohar [54], the review of safety culture theory and literature by Guldenmund [55] from a social-organizational psychology viewpoint, the reciprocal model of safety culture based on social cognitive theory [56], and the review of safety climate measurement scales by Flin et al. [57]. The cluster also contains studies in various industry sectors linking safety culture with safety management systems [58], management practices and accident statistics [59], and safety behaviors [60].

The purple cluster is labelled '*SMS evaluation and performance*', and contains studies and review articles about the effectiveness of safety management systems in various industries. Influential work in this line of research is published by Fernández-Muñiz et al. [61] who used survey research methods in a diverse population of Spanish firms to test the relation between SMS and safety, competitiveness, and economic performance. Bottani et al. [62] performed a survey among Italian manufacturing companies focusing on the relation between SMS and various safety-related practices. The earlier review article by Robson et al. [12] on the effectiveness of occupational health and safety management systems from a safety and economic performance viewpoint is the most highly-cited work in this line of work. Another impactful area of research in this cluster are analysis of essential components of SMS for reducing occupational accidents [63] or in process safety contexts [64]. This is closely related to research proposing SMS performance evaluation models or auditing tools, in which work by Teo and Ling [65] and Chang and Liang [67] is influential.

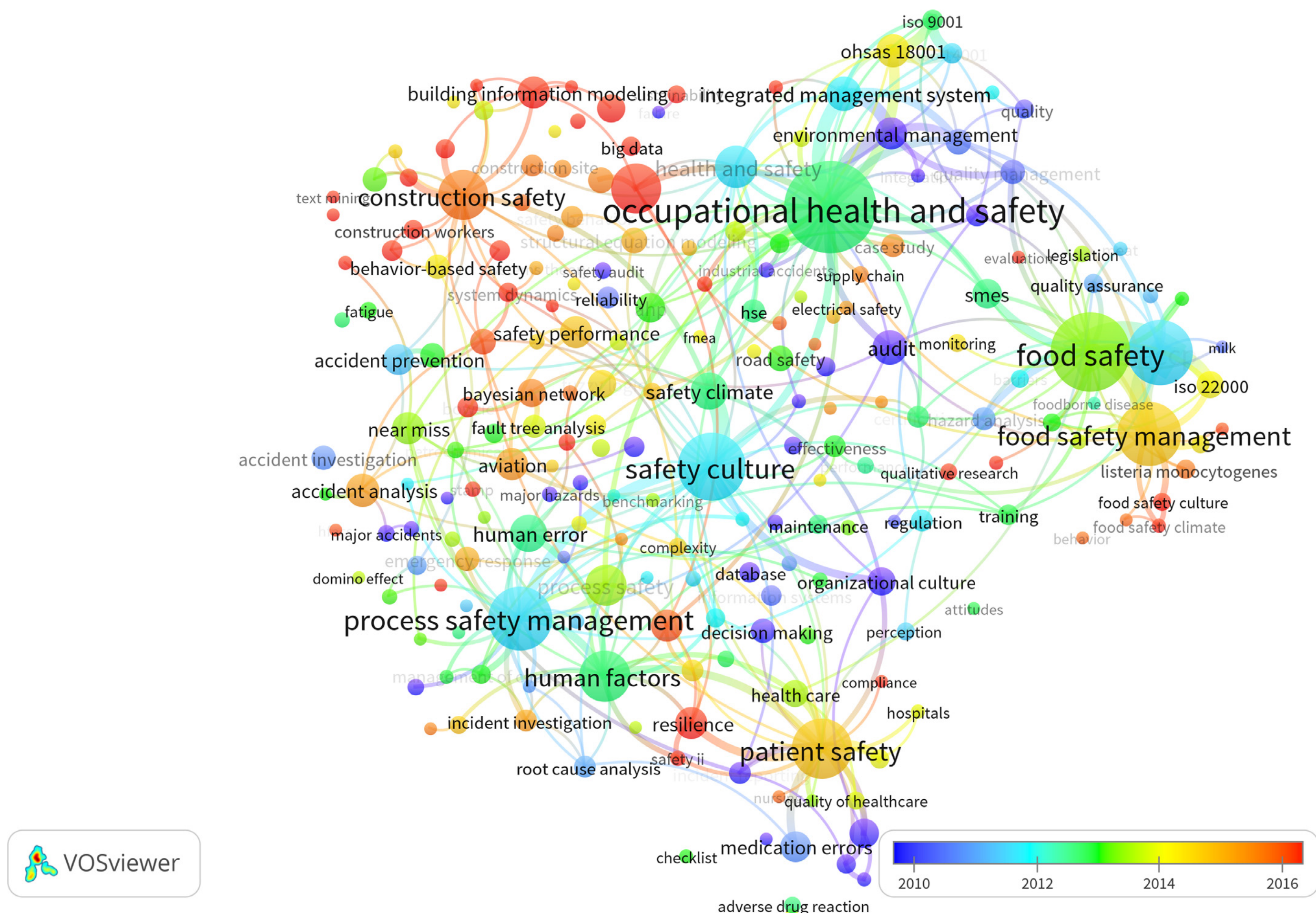

Fig. 9. Average publication year of keywords in safety management system research, keywords which appeared at least 5 times, visualized using VOSviewer [35].

The red cluster focuses on the construction application domain, and is labelled '*Construction industry safety management systems*'. Its most influential cited publication is a newer edition of Heinrich's accident causation theory [68]. The cluster also gives significant weight to studies detailing contributing factors [69] or root causes [70] of construction accidents, with theoretical underpinnings in linear accident causation models such as Heinrich's domino theory and an associated focus on unsafe acts and conditions rooted in organizational shortcomings. The related empirical studies by Tam et al. [71] and Choudhry and Fang [72], focus on the reasons or mechanisms involved in workers' unsafe behaviors at construction sites. Other studies focused on the success factors underlying construction safety performance, based on accident records [73] or survey research [74]. Other influential work focuses on the effectiveness of hazard identification methods to detect 'all known hazards' [75] which led to a proposal of using information technology approaches to improve hazard identification, with Carbonari et al. [76] presenting a prototype system for such proactive safety management. Moving away from approaches based on linear accident causation models, the work by Mitropoulos et al. [77] suggests a new systems-based accident causation model for construction safety, which takes reduction of task unpredictability through production planning and error management as central tenets. Finally, the work on defining leading indicators for construction safety management by Hinze et al. [96] is also influential in the construction safety application domain.

Finally, the blue cluster is also focused on a specific application domain and is labelled '*Food industry safety management systems*'. Food safety management systems are based on good hygienic practices and application of methods such as Hazard Analysis Critical Control Point (HACCP) to attain safe levels of microorganisms in food products. Early influential work focused on the various barriers to implementing HACCP [78,79], and the development of standards and their associated implementation challenges [80,81]. Subsequently, influential work has focused on the development of an instrument to assess the performance of safety control activities [82] and a microbial assessment scheme to assess the microbial performance of a food SMS [83]. Thereafter, influential work focused on elucidating the core assurance activities of a company's food SMS [84], on developing performance indicators to benchmark food safety outcomes of food business without performing microbiological analysis but instead relying on elements related to the SMS [85], and on context factors affecting food safety beyond the food SMS [86].

4. Discussion

4.1. Interpretation of the results and future research directions

The dramatic increase in research outputs on safety management system research since its inception in the late 1970s is remarkable. This increase is likely partially due to SMSs having become important mechanisms for safety assurance and certification in many industrial domains, as observed, e.g., by Li and Guldenmund [8]. Nevertheless, the fast upward trend in SMS research outputs should also be seen in the light of an overall trend in academic publishing of increased publication numbers [87], which is also observed in other safety-related topics such as safety culture [22], construction safety [30], and process safety [21]. Moreover, it is questionable to what extent the dramatic increase in SMS re-

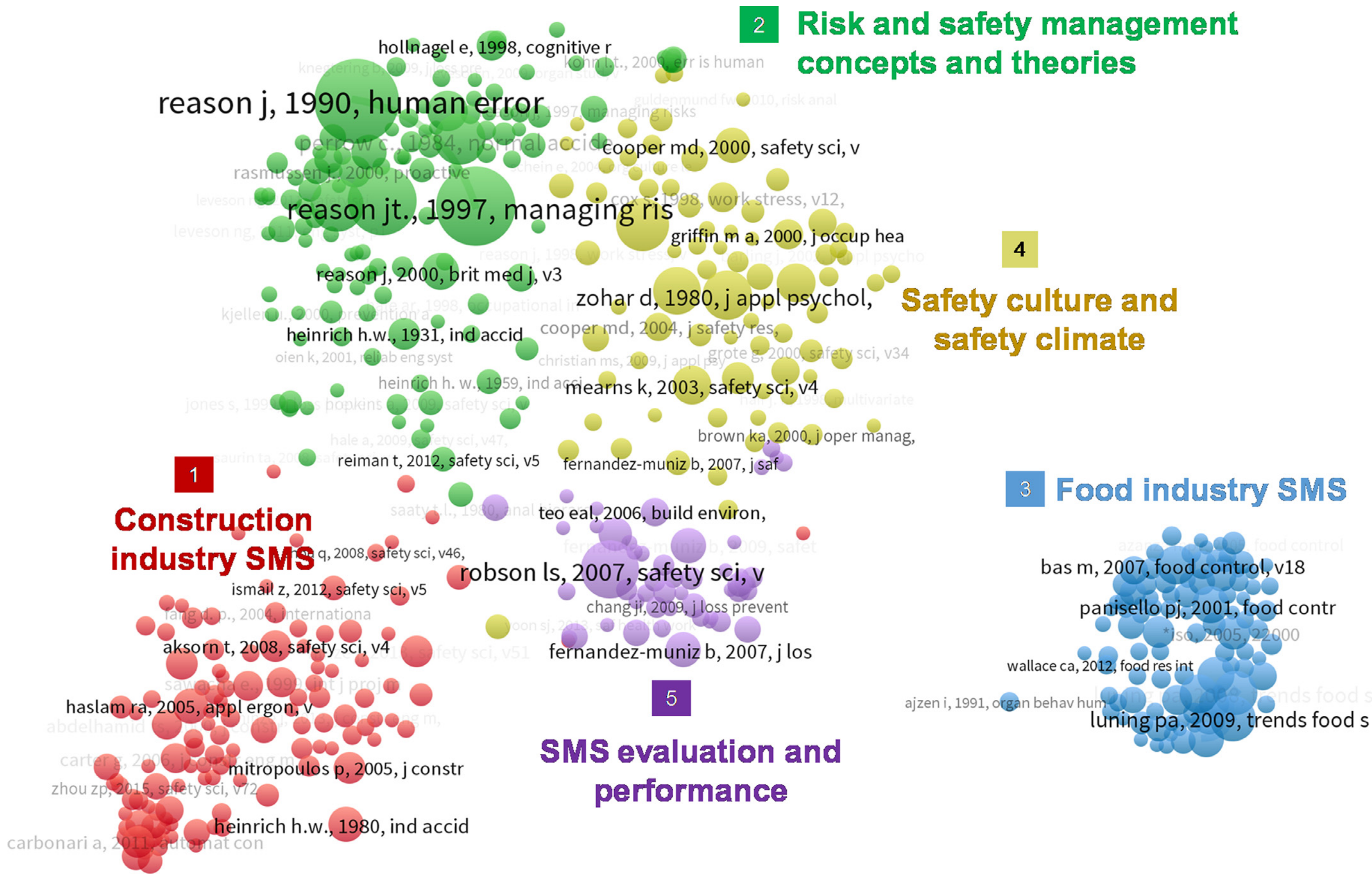

Fig. 10. References co-citation network of safety management systems research, documents cited at least 10 times, visualized using VOSviewer [35].

search volume contributes to changing industrial practices, e.g., Swuste et al. [19] find that few safety science research insights contribute to changes in practical knowledge or implementation. Hence, it would be an interesting area for future research to assess to what extent SMS research developments have impacted industrial practices, how this was facilitated, and whether this was ultimately successful and why.

The very large body of research on SMS enables obtaining insights into some high-level trends and developments. First, whereas the results of Section 3.2.1 show that SMS research originated from the USA, the UK, and the Netherlands, with associated clusters in North America and Western and Southern Europe, there is an ongoing shift in highly productive geographical areas, with China, Australia, and South Korea the most important recent contributors. However, research from South America, Africa, and Central Asia is largely lacking, which may be an area for future scholarship.

Another insight concerns institutional collaborations, as per the results of Section 3.2.2. While there are some longstanding institutional research collaborations, especially related to SMS in the food industries, the overall picture of SMS research is one where many institutions have been or are active, without having established very strong research collaboration links. This observation may relate to the fact that proposing new approaches for safety management systems, or for performing case studies in particular organizations, does not necessarily require international collaboration. Most institutions moreover have published only a limited number of articles on SMS, implying that there is little enduring institutional focus on SMS. This may contribute to the observations by Swuste et al. [19] in a review of occupational safety management that there have been no new theories published on accident processes, and that the quality of SMS research is generally poor. A lack of strong institutional focus on SMS may also lead to an enduring stasis of the research domain, where despite the large research volumes published, there are no significantly new theories or practices developed, or scientifically important new insights obtained.

Another view on the evolution of the SMS research domain is obtained by inspecting the contributions of various scientific domains and journals, and by considering the key contributions. From Section 3.3, it is apparent that the most contributing scientific categories are in applied fields of science, with industrial engineering and operations research and management science the most important ones. Other scientific categories are mostly associated with the application domains in which SMSs are studied or for which developments are made, for instance chemical, food, construction, or transportation industries. This applied and industrial focus of SMS research is of course understandable, but these results also show that the field is not strongly influenced by contributions from more basic scientific disciplines. In contrast, for instance the risk perception [26] and (to a lesser extent) risk communication research domains [89] are based more directly on scientific categories such as '*Social sciences, interdisciplinary*', '*Psychology, multidisciplinary*', '*Psychology, applied*', '*Psychology, social*', '*Psychology*', *and* '*Management*', i.e. on more basic science-oriented scholarship. Scientometric analyzes of those research domains (based on co-citation clusters and associated research fronts) show that there have been progressive theoretical developments in these domains over time, apart from applied research focusing on specific risk issues. This suggests that the SMS research domain may benefit from drawing more directly from journals and other knowledge sources associated with such a more basic science orientation, although in practice that may be hard to achieve [90].

Additionally, the results of Section 3.3.2 show that there are strong dominant patterns in the knowledge flow between journals, and that the bulk of the SMS related literature is published in a rather limited set of journals. The results of Tables 1 and 7 imply that the top 20 most productive journals (2.8% of all sources) contribute over 44% of all published documents on SMS. Such a knowledge concentration can be beneficial to building a scientific community and for legitimizing and delineating the scope of academic journals [91], and for establishing a core knowledge basis e.g. for designing curricula for safety education programs [92,93]. However, such concentration can also lead to a decrease in exposure to and adoption of new ideas, which is an interdisciplinary domain such as safety science appears important. Referring again to the observations by Swuste et al. [19], this provides further weight to directing future research to incorporate research findings, theories, or concepts from journals associated with basic science knowledge domains, as this may reinvigorate the SMS research domain.

Focusing on the narrative clusters as obtained in Section 3.4, it is noteworthy that SMS research in transportation contexts does not constitute a significant cluster, although '*Transportation*' and '*Transportation Science & Technology*' are moderately productive scientific categories as seen in Table 5, and even though SMSs are widely used also in air, rail, maritime, and road transport sectors [94]. Furthermore, from Fig. 8 it is apparent that there are different dominant conceptual and methodological underpinnings in the main SMS application domains (food, healthcare, construction, and process industries). For instance, patient safety has a recent focus on resilience and safety-2, i.e., understanding safety as positive capacities as in resilience engineering [88]. In contrast, SMSs in the process industries focus more on accident and incident analysis, near misses, and human error, and have stronger links with risk analysis methods and approaches. Hence, the dominant conceptual underpinning of this application domain appears more aligned with organizational safety management based on complex linear accident causation models as elaborated by Reason [95]. Referring also to the results of Section 3.5, SMSs in the construction industry has a somewhat similar conceptual view on accident causation as in the process industries, where the work by Heinrich [68] and its legacy in behavior-based safety appears to have a large influence. These findings suggest that, while there is a diverse range of risk and safety management concepts and theories found in these application areas as observed in Fig. 10 and Table 9, they are not equally integrated in the SMS research of the different application domains.

Research on SMS is an important theme in the development of safety science [97]. Therefore, it is useful to situate the results of the current work within a larger context of the development of safety science. Reflecting on the results by [108], who presents a scientometric analysis of the development of the journal *Safety Science*, one of the core journals of the discipline, several issues can be highlighted. First, safety management has been a top-5 research theme since at least the early 2000s, within which SMS has been an influential focus topic, with the work by Robson et al. [12], the most cited one. Second., several key institutions which are found to be highly involved in SMS research are also very influential in *Safety Science*, for instance, Delft University of Technology (Netherlands), Hong Kong Polytechnic University (China), Queensland University of Technology (Australia), and Tsinghua University (China). On a national level, the shift over time in the number of research contributions to SMS originating from the Netherlands, UK, and USA, towards the recently more productive countries such as China, Australia, and South Korea is observed as well in *Safety Science*. Finally, several key themes associated with SMS as found in Section 3.4 are also found as key research topics in *Safety Science*, including safety climate and safety culture, occupational safety, construction safety, road safety, accident analysis, and human factors.

Further reflecting on the results of Figs. 8 and 10, the food SMS research appears to be largely separated from the developments in occupational and process safety SMS research. One marker of this is the significantly different keywords in the food safety cluster and its weak links to other narrative clusters in Fig. 8. Another is its only very recent focus on safety culture and safety climate as seen in Fig. 9, whereas safety culture and climate has been highly integrated to the SMS research in occupational health and safety, process safety and construction safety research domains. It is also evident from the clear separation of the food SMS co-citation cluster in Fig. 10, the highly specific techniques and methods observed in this cluster's key publications in Table 9, and from the information flow between journals in Section 3.3.2. It is understandable that food safety SMS is somewhat separate as it focuses on the safety of food products, through microbiological analyzes and control of production processes, whereas the other SMS application domains focus on human safety or the safety of socio-technical systems. Nevertheless, it may be a fruitful area of future scholarship to make more in-depth comparisons of the contents of the SMSs across application domains, their underlying conceptual and theoretical commitments and their operative contexts, and to understand the reasons why these differences exist. The general SMS framework by Li and Guldenmund [8] may be instrumental to this effect. Such work could lead to a cross-fertilization of ideas, approaches, or best practices, which could lead to further improving SMS performance.

Finally, other selected future directions are mentioned here based on the observations in Section 3. SMSs often rely heavily on bureaucratic approaches to organizational management, which may lead to large safety bureaucracies with negative effects on organizational performance [10]. Hence, future research may focus on approaches and mechanisms to limit the extent of bureaucratic safety work or to make it more efficient, e.g., through machine learning approaches as suggested by Paltrinieri et al. [109] for risk assessment purposes. In construction safety SMS, keywords such as 'big data' may indicate that there is appetite for such developments.

In order to be effective, data-driven approaches likely require an improved understanding of what aspects of SMS design and operation actually improve operational safety. In this context, it is appropriate to highlight that despite the fact that there is some overall evidence that SMS implementation does improve safety performance [12,13], there are open questions as to what elements actually contribute to this and why, whether there are observable differences in organizational (safety) performance for SMSs designed based on different concepts, theories, or methods, and how to align this selection with organizational management styles and work processes, and other contextual (e.g., regulatory) factors. Such future research directions align with earlier made calls for more attention to validation in the general safety sciences [90,110], and in SMS research in particular [20]. In addition, the relevance of such work is confirmed by views from industrial actors, who raise questions about what concepts and tools to choose from the nebulous "safety cloud", and why [111].

In this context, it is important to consider the function of SMSs as part of safety work practices on the one hand, as well as to better understand their role in light of wider organizational objectives and the associated purposes of engaging in particular work activities [112]. It also appears fruitful to consider the design, implementation, and effectiveness of SMS and its components in the context of different work settings characterized by varying levels of flexibility and stability, and associated approaches to uncertainty management [11]. Further considering how SMS can benefit from organizational learning and general management concepts, as well as how organizational change processes influence their functioning, are also avenues for future research [20].

4.2. Study limitations

While the results of Section 3 provide several new insights into the development of SMS research, it is important to be aware of the limitations of the work. First, while scientometric analyzes are well suited to obtain high-level insights into the overall structure and development of a research domain ([21]), they are not well suited for understanding the detailed intricacies of the literature. Depending on the purpose, different types of narrative literature reviews are much better suited for obtaining detailed insights than scientometric techniques [113]. Hence, this work should be considered complementary to recent review articles on SMS, such as [8,20,97]. The insights obtained from the presented analyzes, for instance the development over time of the most

Table 9
Frequently occurring keywords in safety management system research, keywords appearing at least 10 times.

Keywords	Cluster	APY	NP	Keywords	Cluster	APY	NP
aviation	red	2015.18	22	case study	yellow	2015.33	13
accident analysis	red	2015.13	24	ohsas 18001	yellow	2014.21	24
incident investigation	red	2015.08	12	ergonomics	yellow	2013.64	11
emergency response	red	2015.00	14	road safety	yellow	2013.07	15
process safety	red	2013.48	34	iso 9001	yellow	2012.73	11
near miss	red	2013.41	23	occupational health and safety	yellow	2012.66	128
human factors	red	2012.67	49	hse	yellow	2012.62	13
human error	red	2012.55	29	integrated management system	yellow	2011.76	25
process safety management	red	2011.61	71	health and safety	yellow	2011.67	35
root cause analysis	red	2011.08	12	iso 14001	yellow	2011.55	11
accident investigation	red	2010.86	14	quality management system	yellow	2010.67	15
unsafe behavior	green	2018.18	11	quality management	yellow	2010.50	14
internet of things	green	2017.76	18	standards	yellow	2008.08	12
building information modeling	green	2016.86	22	audit	yellow	2006.80	25
construction industry	green	2016.42	47	environmental management	yellow	2006.55	22
simulation	green	2016.10	11	food safety management	purple	2014.57	70
systems thinking	green	2015.73	15	iso 22000	purple	2014.06	17
construction safety	green	2015.49	46	food safety	purple	2013.36	99
construction site	green	2015.45	12	training	purple	2012.82	11
data mining	green	2015.40	16	SMEs	purple	2012.60	20
safety behavior	green	2015.17	12	HACCP	purple	2011.59	73
structural equation modeling	green	2014.93	15	hazard analysis	purple	2011.00	13
safety performance	green	2014.73	22	bowtie	light blue	2016.64	11
behavior-based safety	green	2014.21	14	bayesian network	light blue	2015.44	18
hazard identification	green	2013.21	14	fuzzy logic	light blue	2014.44	18
occupational accidents	green	2012.93	14	vulnerability	light blue	2014.09	11
accident prevention	green	2011.38	21	fault tree analysis	light blue	2013.77	13
resilience	blue	2016.73	22	AHP	light blue	2013.10	20
resilience engineering	blue	2015.73	22	reliability	light blue	2010.58	12
patient safety	blue	2014.68	63	effectiveness	orange	2012.91	12
socio-technical systems	blue	2014.42	12	certification	orange	2012.67	12
health care	blue	2013.53	17	safety climate	orange	2012.62	29
medication errors	blue	2010.86	21	regulation	orange	2011.75	12
information systems	blue	2010.55	11	safety culture	orange	2011.71	77
decision making	blue	2010.07	14	organizational culture	orange	2009.29	18
medical errors	blue	2009.47	19	performance measurement	orange	2008.64	11
incident reporting	blue	2008.92	12				
database	blue	2007.91	11				

Notes: NP = number of publications | APY = average publication year | Cluster = co-occurrence clusters of Fig. 8.

active countries/regions (Section 3.2.1), the contributions to the safety management literature from specific disciplines (Section 3.3.1), and the identified patterns in the references co-citation network with their key associated publications (Section 3.5), could be used as a basis for future narrative literature reviews with a specific associated focus.

A common criticism of scientometric analyzes is the reliance on citation metrics such as the total number of citations to determine impact and for detecting patterns. There are several issues with this. First, citations need time to accumulate, so that citation-based methods are not well suited for detecting more recent development trends, and may lead to undervaluing possible important publications which have not yet had time to attract citations. This may for instance affect the relative importance of keywords in Table 9, especially for subdomains of the research field which have more recently become active. Furthermore, citation-based metrics are controversial as a proxy for the significance of research contributions, see e.g., Garfield [115], because they lend themselves to various types of manipulation [114]. Hence, where important contributors or publications are highlighted as in Section 3.2 or Section 3.5, these results should not be interpreted as an endorsement of the correctness of the work, or as a positive appraisal e.g. concerning its practical usefulness. Instead, it is better to understand the presented scientometric results as descriptive of the research domain, highlighting what countries, institutions, scientific domains, and key publications have shaped the field as it currently is, and how the main narrative patterns and focus topics have changed over time.

A number of specific limitations of the presented work are mentioned. First, the adopted topic-based search strategy shown in Section 2.1 means that a relatively wide set of SMS-related articles is identified and analyzed. Adopting for instance a title-based strategy, using other search terms, or applying a different database of academic publications, will to varying degrees affect the identified literature and hence the results. However, the authors consider the choice of the SCI-EXPANDED and SSCI databases well justified based on the fact that these cover more than 9200 of the world's most impactful journals across over 170 scientific disciplines [116]. Importantly, these include the key safety journals as identified by [117,118], and hence can credibly be conceived to cover the most significant English-language journals publishing on safety management systems. Nevertheless, the restriction to articles published in English can lead to certain biases and blind spots in the analysis, as there are likely also a significant number of articles in other major languages, such as Chinese, Spanish, and Hindi. As these are not included in the analysis, especially the analyzes addressing research trends (Section 3.1) and geographical collaboration patterns (Section 3.2) may lead to different results if other data sets are included as well. This issue of the relevance of the dataset of studied articles is further exacerbated by the fact that safety management systems were originally introduced and conceived as a set of industry best practices, and only later became an object of academic interest and study [20,97]. Hence, there is also a significant body of gray literature on the topic, such as industry and regulatory reports, manuals, guidelines, and books, which is not considered in the current dataset and analysis of development patterns and focus issues. It could be an interesting avenue for future work to compare the focus topics of gray literature with those of the English-language academic work presented in this article, for instance to contribute to closing the gap between industrial and academic actors in safety [119]. Furthermore, an analysis of subsets of the docu-

Table 10
Top 10 most frequently cited publications in the co-citation clusters of safety management system research shown in Fig. 10.

Cited Ref.	Title	NC	Cluster
[68]	Industrial accident prevention: A safety management approach	36	red
[69]	Contributing factors in construction accidents	35	red
[76]	A proactive system for real-time safety management in construction sites	31	red
[74]	Critical success factors influencing safety program performance in Thai construction projects	30	red
[72]	Why operatives engage in unsafe work behavior: Investigating factors on construction sites	30	red
[96]	Leading indicators of construction safety performance	30	red
[77]	Systems model of construction accident causation	30	red
[75]	Safety hazard identification on construction projects	29	red
[73]	Factors affecting safety performance on construction sites	29	red
[70]	Identifying root causes of construction accidents	28	red
[71]	Identifying elements of poor construction safety management in China	28	red
[47]	Human error	132	green
[95]	Managing the risks of organizational accidents	112	green
[51]	Risk management in a dynamic society: A modeling problem	93	green
[52]	A new accident model for engineering safer systems	63	green
[50]	Normal accidents: Living with high-risk technologies	59	green
[88]	Resilience engineering: Concepts and precepts	43	green
[48]	Human error: Models and management	39	green
[53]	Barriers and accident prevention	35	green
[49]	Industrial accident prevention: A scientific approach	31	green
[98]	Proactive risk management in a dynamic society	30	green
[84]	Systematic assessment of core assurance activities in a company specific food safety management system	53	light blue
[82]	Comprehensive analysis and differentiated assessment of food safety control systems: A diagnostic instrument	50	light blue
[78]	Difficulties and barriers for the implementing of HACCP and food safety systems in food businesses in Turkey	41	light blue
[85]	Food safety performance indicators to benchmark food safety output of food safety management systems	40	light blue
[83]	A microbial assessment scheme to measure microbial performance of food safety management systems	38	light blue
[79]	Technical barriers to hazard analysis critical control point (HACCP)	38	light blue
[99]	A tool to diagnose context riskiness in view of food safety activities and microbiological safety output	37	light blue
[80]	ISO 22000:2005 food safety management systems - Requirements for any organization in the food chain	34	light blue
[99]	A concurrent diagnosis of microbiological food safety output and food safety management system performance: Cases from meat processing industries	33	light blue
[81]	Quality and safety standards in the food industry, developments and challenges	32	light blue
[55]	The nature of safety culture: A review of theory and research	63	yellow
[54]	Safety climate in industrial organizations: Theoretical and applied implications	57	yellow
[57]	Measuring safety climate: Identifying the common features	54	yellow
[59]	Safety climate, safety management practice and safety performance in offshore environments	41	yellow
[100]	The impact of organizational climate on safety climate and individual behavior	41	yellow
[56]	Towards a model of safety culture	37	yellow
[58]	Safety management systems and safety culture in aircraft maintenance organisations	31	yellow
[101]	Perceptions of safety at work: A framework for linking safety climate to safety performance, knowledge, and motivation	29	yellow
[102]	Safety culture: Philosopher's stone or man of straw?	28	yellow
[60]	Exploratory analysis of the safety climate and safety behavior relationship	27	yellow
[103]	A study of the lagged relationships among safety climate, safety motivation, safety behavior, and accidents at the individual and group levels	27	yellow
[104]	Organizational safety: Which management practices are most effective in reducing employee injury rates?	27	yellow
[12]	The effectiveness of occupational health and safety management system interventions: A systematic review	71	purple
[63]	Safety management system: Development and validation of a multidimensional scale	36	purple
[61]	Relation between occupational safety management and firm performance	35	purple
[105]	Systematic occupational health and safety management: perspectives on an international development	34	purple
[65]	Developing a model to measure the effectiveness of safety management systems of construction sites	26	purple
[64]	Reviewing the safety management system by incident investigation and performance indicators	24	purple
[106]	Occupational health and safety management in small size enterprises: An overview of the situation and avenues for intervention and research	24	purple
[107]	The analytic hierarchy process: Planning, priority setting, resource allocation	24	purple
[62]	Safety management systems: Performance differences between adopters and non-adopters	23	purple
[67]	Performance evaluation of process safety management systems of paint manufacturing facilities	22	purple

ment types of the dataset, e.g. journal articles or review papers, could be performed.

Second, in the analyzes of temporal evolutions of the developments in the research field, such as in Figs. 3, 5 and 9, the average year of publication of the associated documents is used as a metric to obtain insights. Such averages may hide important information about the shape of the distribution (variance, skewness, etc.), but in scientometric research such averages are commonly used to obtain high-level insights for comparative purposes, see e.g. Li et al. [21].

5. Conclusion

In this work, a scientometric analysis of the academic literature on safety management systems is presented, which spans the period 1979 to 2020 (until April 15). A variety of tools and techniques are applied to detect geographical, structural, and temporal patterns in the research domain. Focus is on contributing countries/regions and institutions, patterns in scientific categories concerned with this research domain, important journals and information flow between journal clusters, narrative themes and focus topics, and knowledge clusters and key contributing documents. Based on the obtained insights, several directions for future research are discussed. The following main conclusions are drawn:

(i) The volume of research outputs on safety management systems has grown exponentially since the first contributions in 1979, with especially since the early 2000s a very significant increase.
(ii) The domain was initially strongly dominated by research from the USA, the UK, and the Netherlands, but in recent years countries such as China, Australia, and South Korea have become very active.
(iii) Few institutions have a sustained research focus on SMSs, and apart from the collaborations between Ghent University and Wageningen University on SMS in the food industries, and to a lesser

extent the collaboration networks of Delft University of Technology, Hong Kong Polytechnic University, and City University of Hong Kong, institutional collaboration networks are not very stable. Especially in China, there is a large number of institutions which have become active in SMS related research in recent years.

(iv) The SMS research domain is highly interdisciplinary, drawing mainly on applied domains of science and with little direct knowledge input from basic sciences. The scientific categories '*Engineering, Industrial*' and '*Operations Research & Management Science*' contributed most to the development of the domain, in addition to categories associated with application-specific knowledge domains, of which '*Engineering, Chemical*', '*Public, Environmental & Occupational Health*', '*Food Science & Technology*', and '*Engineering, Civil*' are the most prominent ones.

(v) By far the most influential journal in SMS research is *Safety Science*, followed by *Journal of Loss Prevention in the Process Industries, Food Control*, and *Process Safety Progress*. There are strongly focused patterns of information flow between journal clusters, which furthermore show the interdisciplinary nature of the research domain.

(vi) The main narrative clusters in SMS research are associated with the dominant application domains: occupational health and safety, process safety, patient safety, food safety, and construction safety. The academic research of these clusters developed in the sequence in which these are listed. SMS research is also strongly tied to safety culture and safety climate research, and a relatively recent cluster focusing on methods is detected as well.

(vii) While general risk and safety management concepts and theories are an important knowledge cluster underlying the SMS research field, there are differences between the dominant concepts and theories in the different application domains, with for instance patient safety focusing more on resilience, process safety more on complex linear accident causation models, and construction safety more on behavior-based safety.

(viii) The safety culture and climate research has already for a long time been strongly linked with especially occupational health and safety, process safety, and to a lesser extent construction safety. In contrast, SMS research in the food industries have only recently started to explore safety culture and climate.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work.We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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References

[1] A. Hale, B.H.J. Heming, J. Carthey, B. Kirwan, Modeling of safety management systems, Saf. Sci. 26 (1–2) (1997) 121–140, doi:10.1016/S0925-7535(97)00034-9.
[2] N. Mitchison, G.A. Papadakis, Safety management systems under seveso ii: implementation and assessment, J. Loss Prev. Process Ind. 12 (1) (1999) 43–51, doi:10.1016/S0950-4230(98)00036-9.
[3] Z. Ismail, S. Doostdar, Z. Harun, Factors influencing the implementation of a safety management system for construction sites, Saf. Sci. 50 (3) (2012) 418–423, doi:10.1016/j.ssci.2011.10.001.
[4] M. Karakasnaki, P. Vlachopoulos, A. Pantouvakis, N. Bouranta, ISM code implementation: an investigation of safety issues in the shipping industry, WMU J. Marit. Aff. 17 (2018) 461–474, doi:10.1007/s13437-018-0153-4.
[5] J.J.H. Liou, L. Yen, G.-.H. Tzeng, Building an effective safety management system for airlines, J. Air Transp. Manag. 14 (1) (2008) 20–26, doi:10.1016/j.jairtraman.2007.10.002.
[6] T. Kelly, The Role of the Regulator in SMS. Discussion Paper 2017–7. International Transport Forum, Organization for Economic Co-operation and Development, 2017.
[7] A.M. Makin, C. Winder, A new conceptual framework to improve the application of occupational health and safety management systems, Saf. Sci. 46 (6) (2008) 935–948, doi:10.1016/j.ssci.2007.11.011.
[8] Y. Li, F.W. Guldenmund, Safety management systems: a broad overview of the literature, Saf. Sci. 103 (2018) 94–123, doi:10.1016/j.ssci.2017.11.016.
[9] D. Mauriño, Why SMS: an Introduction and Overview of Safety Management Systems. 2017–16. International Transport Forum, Organization for Economic Co-operation and Development, 2017.
[10] S.W.A. Dekker, The bureaucratization of safety, Saf. Sci. 70 (2014) 348–357, doi:10.1016/j.ssci.2014.07.015.
[11] G. Grote, Promoting safety by increasing uncertainty - implications for risk management, Saf. Sci. 71 (B) (2015) 71–79, doi:10.1016/j.ssci.2014.02.010.
[12] L.S. Robson, J.A. Clarke, K. Cullen, A. Bielecky, C. Severin, P.L. Bigelow, E. Irvin, A. Cuyler, Q. Mahood, The effectiveness of occupational health and safety management system interventions: a systematic review, Saf. Sci. 43 (3) (2007) 329–353, doi:10.1016/j.ssci.2006.07.003.
[13] M.J.W. Thomas, A Systematic Review of the Effectiveness of Safety Management Systems, Australian Transport Safety Bureau, 2012 AR-2011-148.
[14] E. Gerede, A study of challenges to the success of the safety management system in aircraft maintenance organizations in Turkey, Saf. Sci. 73 (2015) 106–116, doi:10.1016/j.ssci.2014.11.013.
[15] J. Lappalainen, J. Kuronen, U. Tapaninen, Evaluation of the ISM code in the finnish shipping companies, J. Marit. Res. 9 (1) (2012) 23–32.
[16] L. Macheka, F.A. Manditsera, R.T. Ngadze, J. Mubaiwa, L.K. Nyanga, Barriers, benefits and motivation factors for the implementation of food safety management system in the food sector in Harare Province, Zimbabwe, Food Control 34 (1) (2013) 126–131, doi:10.1016/j.foodcont.2013.04.019.
[17] L. Jacxsens, P.A. Luning, W.J. Marcelis, T. van Boekel, J. Rovira, S. Oses, M. Kousta, E. Drosinos, V. Jasson, M. Uyttendaele, Tools for the performance assessment and improvement of food safety management systems, Trends Food Sci. Technol. 22 (2011) S80–S89, doi:10.1016/j.tifs.2011.02.008.
[18] S. Couto da Silva, F.G. Amaral, Critical factors of success and barriers to the implementation of occupational health and safety management systems: a systematic review of literature, Saf. Sci. 117 (2019) 123–132, doi:10.1016/j.ssci.2019.03.026.
[19] P. Swuste, C. van Gulijk, J. Groeneweg, F.W. Guldenmund, W. Zwaard, S. Lemkowitz, Occupational safety and safety management between 1988 and 2010: review of safety literature in English and Dutch language scientific literature, Saf. Sci. 121 (2020) 303–318, doi:10.1016/j.ssci.2019.08.032.
[20] P. Swuste, J. Groeneweg, C. van Gulijk, W. Zwaard, S. Lemkowitz, Y. Oostendorp, The future of safety science, Saf. Sci. 125 (2020) 104593, doi:10.1016/j.ssci.2019.104593.
[21] J. Li, F. Goerlandt, G. Reniers, Mapping process safety: a retrospective scientometric analysis of three process safety related journals (1999–2018), J. Loss Prev. Process Ind. 65 (2020) 104141, doi:10.1016/j.jlp.2020.104141.
[22] K. van Nunen, J. Li, G. Reniers, K. Ponnet, Bibliometric analysis of safety culture research, Saf. Sci. 108 (2018) 248–258.
[23] J. Tao, F. Yang, D. Qiu, G. Reniers, Analysis of safety leadership using a science mapping approach, Process Saf. Environ. Prot. (2020), doi:10.1016/j.psep.2020.04.031.
[24] X. Zou, H.L. Vu, Mapping the knowledge domain of road safety studies: a scientometric analysis, Accid. Anal. Prev. 132 (2019) 105243.
[25] L.A. Ellis, K. Churruca, R. Clay-Williams, C. Pomare, E.E. Austin, J.C. Long, A. Grødah, J. Braithwaite, Patterns of resilience: a scoping review and bibliometric analysis of resilient health care, Saf. Sci. 118 (2019) 241–257.
[26] F. Goerlandt, J. Li, G. Reniers, The landscape of risk perception research: a scientometric analysis, Sustainability 13 (23) (2021) 13188.
[27] M.T. Amin, F. Khan, P. Amyotte, A bibliometric review of process safety and risk analysis, Process Saf. Environ. Prot. 126 (2019) 366–381.
[28] J. Li, F. Goerlandt, G. Reniers, C. Feng, Y. Liu, Chinese international process safety research: collaborations, research trends, and intellectual basis, J. Loss Prev. Process Ind. 74 (2022) 104657.
[29] J. Li, G. Reniers, V. Cozzani, F. Khan, A bibliometric analysis of peer-reviewed publications on domino effects in the process industry, J. Loss Prev. Process Ind. 49 (A) (2017) 103–110, doi:10.1016/j.jlp.2016.06.003.
[30] R. Jin, P.X.W. Zou, P. Piroozfar, H. Wood, Y. Yang, L. Yan, Y. Han, A science mapping approach based review of construction safety research, Saf. Sci. 113 (2019) 285–297, doi:10.1016/j.ssci.2018.12.006.
[31] Y. Wang, H. Cheng, B. Liu, M. Yang, Q. Long, A systematic review on the research progress and evolving trends of occupational health and safety management: a bibliometric analysis of mapping knowledge domains, Front Public Health 8 (2020) 81, doi:10.3389/fpubh.2020.00081.
[32] M. Gil, K. Wróbel, J. Montewka, F. Goerlandt, A bibliometric analysis and systematic review of shipboard decision support systems for accident prevention, Saf. Sci. 128 (2020) 104717, doi:10.1016/j.ssci.2020.104717.

[33] M. Aria, C. Cuccurullo, Bibliometrix: an R-tool for comprehensive science mapping analysis, Informetrics 11 (4) (2017) 959–975.
[34] J.A. Moral-Muñoz, E. Herrera-Viedma, A. Santisteban-Espejo, M.J. Cobo, Software tools for conducting bibliometric analysis in science: an up-to-date review, Prof. Inf. 29 (1) (2020) e290103, doi:10.3145/epi.2020.ene.03.
[35] N.J. Van Eck, L. Waltman, VOSviewer, a computer program for bibliometric mapping, Scientometrics 84 (2) (2010) 523–538.
[36] S. Carley, A.L. Porter, I. Rafols, L. Leydesdorff, Visualization of disciplinary profiles: enhanced science overlay maps, J. Data Inf. Sci. 2 (3) (2017) 68–111.
[37] C. Chen, Citespace Ii: detecting and visualizing emerging trends and transient patterns in scientific literature, J. Am. Soc. Inf. Sci. Technol. 57 (3) (2006) 359–377.
[38] C. Chen, L. Leydesdorff, Patterns of connections and movements in dual-map overlays: a new method of publication portfolio analysis, J. Am. Soc. Inf. Sci. 65 (2) (2014) 334–351.
[39] H. Small, Co-citation in the scientific literature: a new measure of the relationship between two documents, J. Am. Soc. Inf. Sci. 24 (4) (1973) 265–269.
[40] O. Persson, The intellectual base and research fronts of jasis 1986–1990, J. Am. Soc. Inf. Sci. 45 (1) (1994) 31–38.
[41] M.A. Ayoub, Integrated safety management information system part i: design and architecture, J. Occup. Accid. 2 (2) (1979) 135–157, doi:10.1016/0376-6349(79)90005-1.
[42] M.A. Ayoub, Integrated safety management information system part ii: allocation of resources, J. Occup. Accid. 2 (3) (1979) 191–208, doi:10.1016/0376-6349(79)90009-9.
[43] D.D. Beaver, Reflections on scientific collaboration (and its study): past, present, and future, Scientometrics 52 (2001) 365–377.
[44] Z. Chinchilla-Rodríguez, S. Miguel, A. Perianes-Rodríguez, C.R. Sugimoto, Dependencies and autonomy in research performance: examining nanoscience and nanotechnology in emerging countries, Scientometrics 115 (2018) 1485–1504.
[45] A. Stirling, A general framework for analysing diversity in science, technology and society, J. R. Soc. Interface 4 (15) (2007) 707–719.
[46] M.C. Kim, Y. Zhu, C. Chen, How are they different? A quantitative domain comparison of information visualization and data visualization (2000–2014), Scientometrics 107 (2016) 123–165.
[47] J. Reason, Human Error, Cambridge University Press, 1990.
[48] J. Reason, Human error: models and managament, Br. Med. J. 320 (2000) 768.
[49] H.W. Heinrich, Industrial Accident Prevention: A Scientific Approach, McGraw-Hill, New York, USA, 1931.
[50] C. Perrow, Normal Accidents: Living with High-Risk Technologies, Basic Books, New York, USA, 1984.
[51] J. Rasmussen, Risk managament in a dynamic society: a modeling problem, Saf. Sci. 27 (2–3) (1997) 183–213.
[52] N. Leveson, A new accident model for engineering safer systems, Saf. Sci. 42 (4) (2004) 237–270, doi:10.1016/s0925-7535(03)00047-x.
[53] E. Hollnagel, Barriers and Accident Prevention, Ashgate, Aldershot, Hampshire, UK, 2004.
[54] D. Zohar, Safety Climate in industrial organizations: theoretical and applied implications, J. Appl. Psychol. 65 (1) (1980) 96–102, doi:10.1037/0021-9010.65.1.96.
[55] F.W. Guldenmund, The nature of safety culture: a review of theory and research, Saf. Sci. 34 (1–3) (2000) 215–257, doi:10.1016/s0925-7535(00)00014-x.
[56] M.D. Cooper, Towards a model of safety culture, Saf. Sci. 36 (2) (2000) 111–136, doi:10.1016/s0925-7535(00)00035-7.
[57] R. Flin, K. Mearns, P. O'Connor, R. Bryden, Measuring safety climate: identifying the common features, Saf. Sci. 34 (1–3) (2000) 177–192, doi:10.1016/s0925-7535(00)00012-6.
[58] N. McDonald, S. Corrigan, C. Daly, S. Cromie, Safety management systems and safety culture in aircraft maintenance organisations, Saf. Sci. 34 (1–3) (2000) 151–176, doi:10.1016/s0925-7535(00)00011-4.
[59] K. Mearns, S.M. Whitaker, R. Flin, Safety climate, safety management practice and safety performance in offshore environments, Saf. Sci. 41 (8) (2003) 641–680, doi:10.1016/s0925-7535(02)00011-5.
[60] M.D. Cooper, R.A. Phillips, Exploratory analysis of the safety climate and safety behavior relationship, J. Saf. Res. 35 (5) (2004) 497–512, doi:10.1016/j.jsr.2004.08.004.
[61] B. Fernandez-Muniz, J.M. Montes-Peon, C.J. Vazquez-Ordas, Relation between occupational safety management and firm performance, Saf. Sci. 47 (7) (2009) 980–991, doi:10.1016/j.ssci.2008.10.022.
[62] E. Bottani, L. Monica, G. Vignali, Safety management systems: performance differences between adopters and non-adopters, Saf. Sci. 47 (2) (2009) 155–162, doi:10.1016/j.ssci.2008.05.001.
[63] B. Fernández-Muñiz, J.M. Montes-Peón, C.J. Vázquez-Ordás, Safety management system: development and validation of a multidimensional scale, J. Loss Prev. Process Ind. 20 (1) (2007) 52–68, doi:10.1016/j.jlp.2006.10.002.
[64] B. Basso, C. Carpegna, C. Dibitonto, G. Gaido, A. Robotto, C. Zonato, Reviewing the safety management system by incident investigation and performance indicators, J. Loss Prev. Process Ind. 17 (3) (2004) 225–231, doi:10.1016/j.jlp.2004.02.004.
[65] E.A.L. Teo, F.Y.Y. Ling, Developing a model to measure the effectiveness of safety management systems of construction sites, Build. Environ. 41 (11) (2006) 1584–1592, doi:10.1016/j.buildenv.2005.06.005.
[66] J. Li, F. Goerlandt, G. Reniers, An Overview of Scientometric Mapping for the Safety Science Community: Methods, Tools, and Processes, Safety Science 134 (2021) 105093.
[67] J.J. Chang, C.L. Liang, Performance evaluation of process safety management systems of paint manufacturing facilities, J. Loss Prev. Process Ind. 22 (4) (2009) 398–402, doi:10.1016/j.jlp.2009.02.004.
[68] H.W. Heinrich, Industrial Accident Prevention: A Safety Management Approach, McGraw Hill Text, 1980.
[69] R.A. Haslam, S.A. Hide, A.G.F. Gibb, D.E. Gyi, T. Pavitt, S. Atkinson, A.R. Duff, Contributing factors in construction accidents, Appl. Ergon. 36 (4) (2005) 401–415, doi:10.1016/j.apergo.2004.12.002.
[70] T.S. Abdelhamid, J.G. Everett, Identifying root causes of construction accidents, J. Constr. Eng. Manag. 126 (1) (2000) 52–60, doi:10.1061/(asce)0733-9364(2000)126:1(52).
[71] C.M. Tam, S.X. Zeng, Z.M. Deng, Identifying elements of poor construction safety management in China, Saf. Sci. 42 (7) (2004) 569–586, doi:10.1016/j.ssci.2003.09.001.
[72] R.M. Choudhry, D. Fang, Why operatives engage in unsafe work behavior: investigating factors on construction sites, Saf. Sci. 46 (4) (2008) 566–584, doi:10.1016/j.ssci.2007.06.027.
[73] E. Sawacha, S. Naoum, D. Fong, Factors affecting safety performance on construction sites, Int. J. Proj. Manag. 17 (5) (1999) 309–315, doi:10.1016/s0263-7863(98)00042-8.
[74] T. Aksorn, B.H.W. Hadikusumo, Critical success factors influencing safety program performance in thai construction projects, Saf. Sci. 46 (4) (2008) 709–727, doi:10.1016/j.ssci.2007.06.006.
[75] G. Carter, S.D. Smith, Safety hazard identification on construction projects, J. Constr. Eng. Manag. 132 (2) (2006) 197–205, doi:10.1061/(asce)0733-9364(2006)132:2(197).
[76] A. Carbonari, A. Giretti, B. Naticchia, A proactive system for real-time safety management in construction sites, Autom. Constr. 20 (6) (2011) 686–698, doi:10.1016/j.autcon.2011.04.019.
[77] P. Mitropoulos, T.S. Abdelhamid, G.A. Howell, Systems model of construction accident causation, J. Constr. Eng. Manag. 131 (7) (2005) 816–825, doi:10.1061/(asce)0733-9364(2005)131:7(816).
[78] M. Baş, M. Yüksel, T. Çavuşoğlu, Difficulties and barriers for the implementing of HACCP and food safety systems in food businesses in Turkey, Food Control 18 (2) (2007) 124–130, doi:10.1016/j.foodcont.2005.09.002.
[79] P.J. Panisello, P.C. Quantick, Technical barriers to hazard analysis critical control point (HACCP), Food Control 12 (3) (2001) 165–173, doi:10.1016/s0956-7135(00)00035-9.
[80] ISOISO 22000:2005 Food Safety Management Systems - Requirements for Any Organization in the Food Chain, International Organization for Standardization, 2005.
[81] J. Trienekens, P. Zuurbier, Quality and safety standards in the food industry, developments and challenges, Int. J. Prod. Econ. 113 (1) (2008) 107–122, doi:10.1016/j.ijpe.2007.02.050.
[82] P.A. Luning, L. Bango, J. Kussaga, J. Rovira, W.J Marcelis, Comprehensive analysis and differentiated assessment of food safety control systems: a diagnostic instrument, Trends Food Sci. Technol. 19 (10) (2008) 522–534, doi:10.1016/j.tifs.2008.03.005.
[83] L. Jacxsens, J. Kussaga, P.A. Luning, M. Van der Spiegel, F. Devlieghere, M. Uyttendaele, A microbial assessment scheme to measure microbial performance of food safety management systems, Int. J. Food Microbiol. 131 (1–2) (2009) 113–125, doi:10.1016/j.ijfoodmicro.2009.02.018.
[84] P.A. Luning, W.J. Marcelis, J. Rovira, M. Van der Spiegel, M. Uyttendaele, L. Jacxsens, Systematic assessment of core assurance activities in a company specific food safety management system, Trends Food Sci. Technol. 20 (6–7) (2009) 300–312, doi:10.1016/j.tifs.2009.03.003.
[85] L. Jacxsens, M. Uyttendaele, F. Devlieghere, J. Rovira, S.O. Gomez, P.A Luning, Food safety performance indicators to benchmark food safety output of food safety management systems, Int. J. Food Microbiol. 141 (2010) S180–S187, doi:10.1016/j.ijfoodmicro.2010.05.003.
[86] P.A. Luning, L. Jacxsens, J. Rovira, S.M. Osés, M. Uyttendaele, W.J. Marcelis, A concurrent diagnosis of microbiological food safety output and food safety management system performance: cases from meat processing industries, Food Control 22 (3–4) (2011) 555–565, doi:10.1016/j.foodcont.2010.10.003.
[87] M. Ware, M. Mabe, The Stm Report: An Overview of Scientific and Scholarly Journal Publishing, International association of scientific, technical and medical publishers, The Hague, Netherlands, 2015.
[88] E. Hollnagel, D.D. Woods, N. Leveson, Resilience Engineering: Concepts and Precepts, CRC Press, 2006.
[89] F. Goerlandt, J. Li, G. Reniers, The landscape of risk communication research: a scientometric analysis, Int. J. Environ. Res. Public Health 17 (2020) 3255, doi:10.3390/ijerph17093255.
[90] A. Hale, Foundations of safety science: a postscript, Saf. Sci. 67 (2014) 64–69, doi:10.1016/j.ssci.2014.03.001.
[91] T. Aven, What is safety science? Saf. Sci. 67 (2014) 15–20, doi:10.1016/j.ssci.2013.07.026.
[92] P.M. Arezes, P. Swuste, Occupational health and safety post-graduation courses in europe: a general overview, Saf. Sci. 50 (3) (2012) 433–442, doi:10.1016/j.ssci.2011.10.003.
[93] B. Wang, C. Wu, J. Li, L. Zhang, L. Huang, L. Kang, Certified safety engineer (CSE) as a new official profession in china: a brief review, Saf. Sci. 116 (2019) 108–115, doi:10.1016/j.ssci.2019.03.007.
[94] ITFSafety Management Systems. International Transport Forum Roundtable Report, OECD Publishing, Paris, 2018.
[95] J. Reason, Managing the Risks of Organizational Accidents, Ashgate, Hampshire, England, 1997.
[96] J. Hinze, S. Thurman, A. Wehle, Leading indicators of construction safety performance, Saf. Sci. 51 (1) (2013) 23–28, doi:10.1016/j.ssci.2012.05.016.
[97] P. Swuste, J. Groeneweg, C. van Gulijk, W. Zwaard, S. Lemkowitz, Safety management systems from three mile island to piper alpha, a review in English and

Dutch literature for the period 1979 to 1988, Saf. Sci. 107 (2018) 224–244, doi:10.1016/j.ssci.2017.06.003.
[98] J. Rasmussen, I. Svedung, Proactive Risk Management in a Dynamic Society, Sjuhäradsbygdens Tryckeri, Borås, Sweden, 2000.
[99] P.A. Luning, W.J. Marcelis, J. Rovira, M.A.J.S. van Boekel, M. Uyttendaele, L. Jacxsens, A tool to diagnose context riskiness in view of food safety activities and microbiological safety output, Trends Food Sci. Technol. 22 (2011) S67–S79, doi:10.1016/j.tifs.2010.09.009.
[100] A. Neal, M.A. Griffin, P.M. Hart, The impact of organizational climate on safety climate and individual behavior, Saf. Sci. 34 (1–3) (2000) 99–109, doi:10.1016/s0925-7535(00)00008-4.
[101] M.A. Griffin, A. Neal, Perceptions of safety at work: a framework for linking safety climate to safety performance, knowledge, and motivation, J. Occup. Health Psychol. 5 (3) (2000) 347–358, doi:10.1037/1076-8998.5.3.347.
[102] S. Cox, R. Flin, Safety culture: philosopher's stone or man of straw? Work Stress 12 (3) (1998) 189–201 An International Journal of Work, Health & Organizations, doi:10.1080/02678379808256861.
[103] A. Neal, M.A. Griffin, A study of the lagged relationships among safety climate, safety motivation, safety behavior, and accidents at the individual and group levels, J. Appl. Psychol. 91 (4) (2006) 946–953, doi:10.1037/0021-9010.91.4.946.
[104] A.G. Vredenburgh, Organizational safety: which management practices are most effective in reducing employee injury rates? J Safety Res 33 (2) (2002) 259–276, doi:10.1016/s0022-4375(02)00016-6.
[105] K. Frick, P. Jensen, M. Quinlan, T. Wilthagen, Systematic Occupational Health and Safety Management: Perspectives on an International Development, Pergamon Press, Oxford, UK, 2000.
[106] D. Champoux, J.-.P. Brun, Occupational health and safety management in small size enterprises: an overview of the situation and avenues for intervention and research, Saf. Sci. 41 (4) (2003) 301–318, doi:10.1016/S0925-7535(02)00043-7.
[107] T.L. Saaty, The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation, McGraw-Hill, 1980.
[108] J.M. Merigó, J. Miranda, N.M. Modak, G. Boustras, C. de la Sotta, Forty years of safety science: a bibliometric overview, Saf. Sci. 115 (2019) 66–88.
[109] N. Paltrinieri, L. Comfort, G. Reniers, Learning about risk: machine learning for risk assessment, Saf. Sci. 118 (2019) 475–486, doi:10.1016/j.ssci.2019.06.001.
[110] J.-.C. Le Coze, K. Pettersen, T. Reiman, The foundations of safety science, Saf. Sci. 67 (2014) 1–5, doi:10.1016/j.ssci.2014.03.002.
[111] edited by O. Guillaume, N. Herchin, C. Neveu, P. Noël, C. Gilbert, H. Laroche, B. Journé, C. Bieder, An industrial view on safety culture and safety models: what to choose and how in the nebulous 'safety cloud' of concepts and tools? In safety cultures, safety models: taking stock and moving forward, in: Springer Briefs in Applied Sciences and Technology, Springer, Cham, Switzerland, 2018, pp. 1–13.
[112] A. Rae, D. Provan, Safety work versus the safety of work, Saf. Sci. 111 (2019) 119–127, doi:10.1016/j.ssci.2018.07.001.
[113] M.J. Grant, A. Booth, A typology of reviews: an analysis of 14 review types and associated methodologies, Health Info. Libr. J. 26 (2009) 91–108.
[114] E.A. Fong, A.W. Wilhite, Authorship and citation manipulation in academic research, PLoS One 12 (2017).
[115] E. Garfield, Is citation analysis a legitimate evaluation tool? Scientometrics 1 (4) (1979) 359–375.
[116] S. Gupta, 2021. Updated list of web of science SCI expanded Journals September-2021 (Latest). doi:10.13140/RG.2.2.27838.41283.
[117] J. Li, A. Hale, Identification of, and knowledge communication among core safety science journals, Saf. Sci. 74 (2015) 70–78.
[118] G. Reniers, Y. Anthone, A ranking of safety journals using different measurement methods, Saf. Sci. 50 (2012) 1445–1451.
[119] T. Reiman, K. Viitanen, C. Le Coze, Towards actionable safety science, in: Safety Science research: Evolution, Challenges and New Directions, CRC Press, Boca Raton, FL, 2020, pp. 203–222.