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Collaboration networks evolution of Safety Science from 1976 to 2019

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ABSTRACT

There is a recent interest to understand the nature of the safety science discipline and to obtain insights in its development patterns and research trends. This article analyzes the evolution of the prevalence and scale of collaborative publishing and the macro-level collaboration scale of the Safety Science research community. Additionally, an analysis of the evolution of influential research topics of the core researchers' collaboration networks provides insights in the domain's high-level development trends. Both the prevalence and scale of scientific collaboration are found to have increased dramatically since the inception *of Journal of Occupational Accidents, Safety Science's* predecessor. Research networks have grown significantly, and collaboration between core researchers has steadily increased. Even though this indicates that a core safety science research community has developed, it is also found that the journal continues to serve as a platform for many small and unconnected author clusters. In terms of influential research topics, there is a notable shift from technical aspects of work safety towards psychological and organizational mechanisms of safety. More recently, influential work of core research networks has additionally focused on safety and risk models and methods, the conceptual and theoretical foundations of the domain, and influential research clusters have formed around safety in specific industries. The focus topics of core researcher's collaboration clusters furthermore highlight the variety of conceptual, theoretical, and methodological approaches co-existing within *Safety Science*. Various implications of the findings are discussed, where both possible benefits and drawbacks of increased collaboration are highlighted and future research avenues outlined.

KEYWORDS

Collaboration network; Co-authorship; Safety Science; Bibliometrics; Scientometrics; VOSviewer

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1 Introduction

In 1976, the *Journal of Occupational Accidents* was established with the objective of promoting multidisciplinary research on the science and technology of human and industrial safety (Merigó et al., 2019). It was renamed in 1991 as *Safety Science*, and currently aims to cover a broad range of human, technological, organizational, and societal aspects of safety in all fields of human activity (Boustras et al., 2020). Various authors have discussed the nature and scope of safety science as an academic discipline, e.g., Aven (2014), Hale (2014), Stoop et al. (2017), and Ge et al. (2019). While safety science is widely regarded as a multidisciplinary field of research, several authors have commented that its scientific diversity leads to fragmentation, a lack of professional identity, and enduring debates about the appropriate scientific paradigms underlying safety work (Le Coze et al., 2014; Ge et al., 2019).

In an effort to better understand the knowledge structure of safety science and its evolution, several authors have made high-level analyses focusing on patterns in the dominant journals, narratives, focus topics, and key knowledge domains contributing to the safety science discipline or its application-specific subdomains, e.g., Reniers and Anthone (2012), Li and Hale (2015; 2016) and Merigó et al. (2019). Scientometric analysis and mapping techniques have become an important method for creating high-level insights in the development of safety science, see Li et al. (2020) for an overview of techniques and safety-related analyses.

An important issue, especially in multidisciplinary domains, is research collaboration. Collaboration at various levels within the research enterprise (individual, institutional, countries/regions) are usually associated with several advantages. These include sharing knowledge and expertise and cross-fertilization of ideas, better coping with increased disciplinary specialization, higher productivity, and visibility (Franceschet & Constantini, 2010). In addition, it is known that core researchers are important in the continued existence, development, and growth of research domains. Such individuals leverage social and other resources to encourage integrative research and innovation, and build, maintain, and expand knowledge domains by producing influential bodies of literature (Abrahams et al., 2019; Wagner & Leydesdorff, 2005). Consequently, several authors have investigated the evolution of research collaboration and core researchers in various scientific disciplines and research fields, e.g., social science (Moody, 2004), computer science (Franceschet, 2011), scientometrics (Zhao & Zhao, 2016), environmental management (Abrahams et al., 2019), and tourism research (Fan et al., 2020).

Considering the above, the purpose of this article is to provide insights in how research collaborations in the safety science domain have evolved over time, and what research topics the domain's core researchers focused on. To delineate this research domain, the focus is here on the published articles in the *Journal of Occupational Accidents* and its successor *Safety Science*. The overall question we aim to answer in this article is: how has the research collaboration in *Safety Science* evolved over time? To answer this general question, we identify the following specific sub-questions: RQ1) what is the evolution in collaborative publishing in *Safety Science*?; RQ2) what is the evolution of the prevalence and scale of collaboration in *Safety Science*?; RQ3) who are the core researchers in *Safety Science* over time?; and RQ4) what are the key research topics of the collaboration networks of these core researchers in *Safety Science*? The answers to these questions are sought through the application of various scientometric analyses and visualizations. The results will contribute to an increased understanding of the evolution of the *safety science* domain and how important research collaborations and core authors have contributed to its development.

The remainder of this article is organized as follows. In Section 2, the data collection process and the methodology for analysis are described. Section 3 shows the analysis results, providing answers to the research questions listed above. A discussion is provided in Section 4, while Section 5 concludes.

2 Data and methods

2.1 Data collection process and resulting dataset

The data were retrieved from the Scopus and Web of Science databases, two of the most comprehensive and high-quality databases of scholarly publications (Li et al., 2020), on March 2, 2020. Since the former name of the *Safety Science* journal is *Journal of Occupational Accidents*, the data from both these source titles are downloaded. Data from *Safety Science* (SS) was downloaded from Web of Science, owned by Clarivate, while data from *Journal of Occupational Accidents* (JOA) data was downloaded from Scopus. This is because data from JOA are not completely indexed in the Web of Science (WoS). In contrast, as Scopus and JOA were owned and published by the same company, Elsevier B.V, Scopus includes all the publication records of JOA.

Original research articles and review papers published in SS and JOA were selected as the data sample because these publication types have a high scientific value compared to document types such as editorials, letters, and errata. The period covered ranges from 1976 up to and including 2019. Within the finally obtained dataset of 4004 publications, 314 records (accounting for 7.8%) originate from JOA, and 3690 records (accounting for 92.2%) are published in SS. Summary information is provided in Table 1, whereas a detailed distribution of the yearly number of records is shown in Fig. 1, along with some descriptive statistics of three development periods that can be identified.

Table 1 Detailed information of the sample data

No.	Journals title	NP	NA	Time period	Data sources
1	Journal of Occupational Accidents (JOA)	314 (7.8%)	344	1976–1990 (15 years)	Scopus
2	Safety Science (SS)	3690 (92.2%)	7723	1991–2019 (29 years)	Web of Science
3	SS and JOA	4004(100%)	7992	1976–2019 (44 years)	WoS format

Notes: NP=Number of publications, NA=Number of authors

Period I coincides with the era when the journal was published under the name *Journal of Occupational Accidents* and spans the period 1976 to 1990. In the 15 years spanning this period, there are 314 articles published, or ca. 20.9 per year on average, which is comparatively low. In **Period II**, which spans the period 1991 to 2007, the journal was published as *Safety Science*. This period is more productive than the former, with a relatively stable annual number of publications of 47.6, amounting to 809 articles in total. In the 17 years spanning this period, there is an observable slight increase in the number of articles, but overall, this era in the history of *Safety Science* is relatively stable. The year 2008 marks the beginning of **Period III** in the publication history of *Safety Science*. In the 12-year period until 2019, there is a very fast increasing trend in the number of publications, with an average of 240.1 articles published per year, a large variance, and a remarkable expansion, especially in the last few years. These three periods will be used as a basis for the analysis of the evolution of research collaboration in subsequent sections.

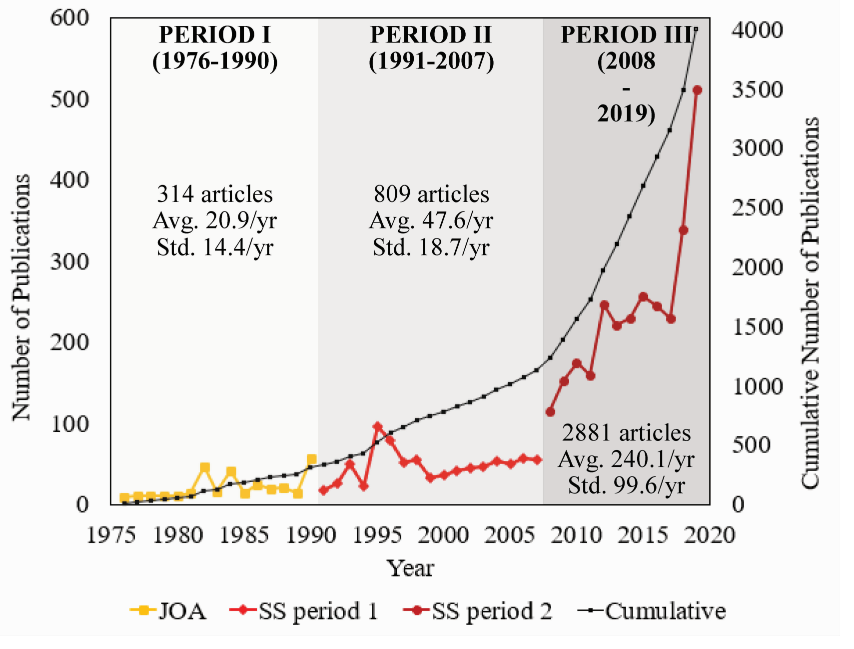


Figure 1 Yearly number of publications in JOA (1976-1990) and SS (1991-2019),summary statistics of three development periods

2.2 Process and methodology

Fig. 2 shows a flowchart of the research process used to obtain answers to the research questions listed in Section 1. The data collection process has been described already in Section 2.1, with data for SS downloaded from Web of Science, and data for JOA from Scopus. An integrated dataset is constructed using the Bibliographic Analysis Tool developed by Li et al. (2020), which is a necessary step to ensure compatibility between the data formats from these two sources. Author name disambiguation is performed as a further pre-processing step. This is necessary because the Web of Science and Scopus databases often contain multiple name formats, especially for prolific writers.

The data analysis process, which leads to the results answering the research questions listed in Section 1, uses different methods and tools to provide results. To obtain insights into the evolution of the prevalence and scale of collaborative publishing (RQ1) and to determine the core researchers (RQ3), simple counts and summary statistics are applied. The scale of collaboration (RQ2) is analyzed using the VOSviewer software (Van Eck & Waltman, 2010) and Gephi (Bastian et al., 2009), a widely-used open source software for exploring networks. The entire collaboration networks in different time periods are visualized, and several descriptive metrics of the network structure and scale are calculated. VOSviewer implements the visualization of similarities method, which constructs a network structure where quantitative metrics indicate the level of closeness between data entries (such as authors) and their relative importance (e.g., in terms of the number of publications authored) (Van Eck & Waltman, 2007). The networks are visualized using the Gephi software, which also allows calculating various network metrics. The networks of the core safety science researchers are subsequently extracted and visualized using Gephi, and the key collaborators and research topics of these core researcher networks are identified (RQ4). This is done using the results of the visualized networks and citation information from the integrated JOA-SS dataset.

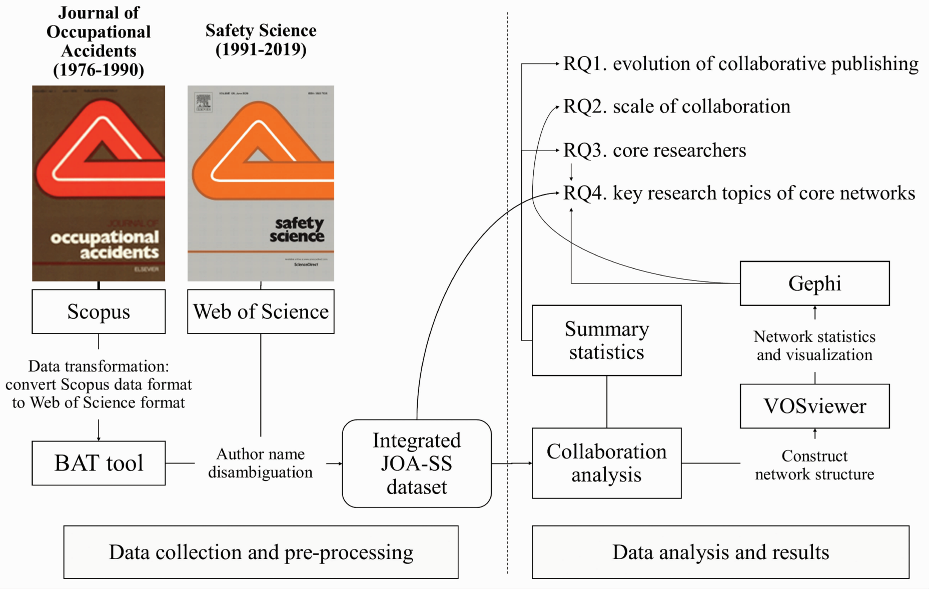


Figure 2 Research process for Safety Science collaboration and core researchers analysis

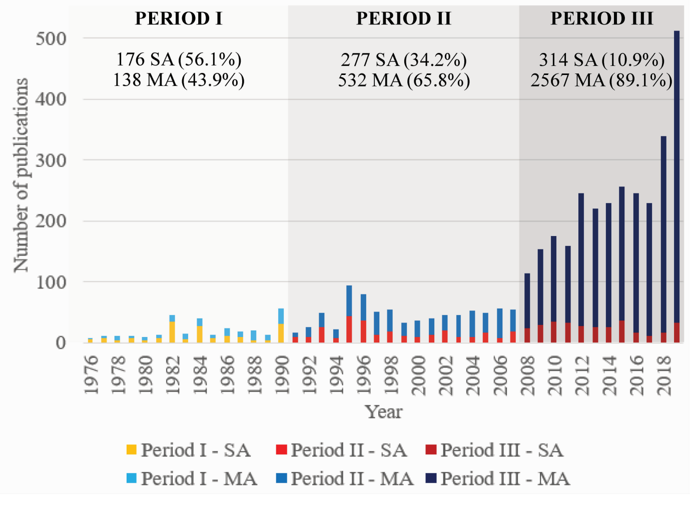
3 Results

3.1 Evolution of number of authors in publications in Safety Science

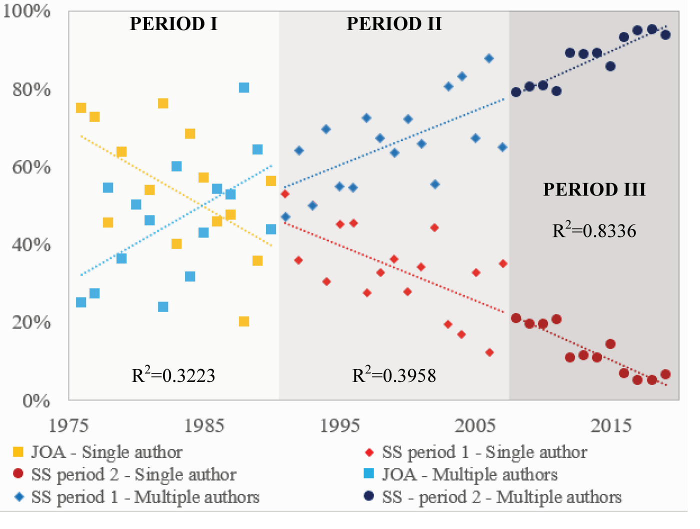
In this Section, results for RQ1 are shown. Research collaboration is a social enterprise, for which co-authorship is widely considered as a reliable proxy (Moody, 2004; Franceschet & Constantini, 2010). Hence, taking publications as units of analysis, two indicators of scientific collaboration are assessed. The first is the trend in the ratio between single-authored versus multi-authored articles by publication year, which provides insights into the temporal evolution of the prevalence of research collaboration. The second is the number of co-authors of articles in different time periods, which provides insights into the scale of collaboration.

In the period 1976-2019, 7922 authors have published a total of 4004 papers in JOA and SS. Fig. 3 represents the annual trends of single-authored and multiple-authored papers, with Fig. 3a showing the absolute numbers of articles and Fig. 3b the ratios. Three periods of the development of *Safety Science* are distinguished, in line with the global publication trends observed in Fig. 1.

In **Period I** (JOA, 1976-1990), with 43.9%, the number of articles with multiple authors is smaller than the number of single-authored articles. A weak increasing trend towards more multi-authored publications can already be observed in this period, but overall, the development of research collaboration is in its initial stages. In **Period II** (SS1, 1991-2007), there is a continued increasing trend in the share of multi-authored articles, with 65.8% of the articles published the results of collaboration. There is a continued, now somewhat stronger, trend towards more research collaboration, which can be said to have become the norm since around the year 2000. In **Period III** (SS2, 2008-2019), the total number of articles increased dramatically, but the number of single-authored articles remained relatively stable. The trend towards increased collaboration is clearly continuing, and the statistical significance of this trend is higher. Consequently, the ratio of multi-authored articles increased from about 80% around 2010 to almost 95% at the end of the period. These results indicate that the research collaboration landscape of *Safety Science* has evolved dramatically over the considered timespan.



(a) Annual number of SA and MA



(b) Ratio of SA and MA and associated trends

Figure 3 Evolution of single author (SA) versus multiple author (MA) articles in JAO (1976-1990) and SS (1991-2019), Periods I-III as in Fig. 1

The number of authors of an article is a further publication-based metric, providing insights into the scale of collaboration. The distribution of the number of authors of articles in *Safety Science* is shown in Fig. 4, with the x-axis representing the team size, and the y-axis the occurrence frequency of articles with a certain number of authors. The analysis is performed for the same time periods as in Section 2.1, to investigate to what extent research collaborations increased in scale over time.

It is seen that in **Period I** (JOA, 1976-1990), most articles were single-authored, with articles with two or three authors markedly less frequent. About 5% of the articles had more than three authors. This shows that the scale of research collaboration was limited and in the initial stages. In **Period II** (SS1, 1991-2007), multi-authored articles became the norm, with respectively 30.0% and 20.3% of the articles having two or three authors. The share of articles with more than three authors increased to 15.5%, with articles with four and five authors no longer a rarity. Nevertheless, single-author articles were still the most frequent type in this period, which can be understood as a developing period for research collaboration. A very different picture is apparent for **Period III** (SS2, 2008-2019). Here, the most frequently occurring number of authors is three (28.0% of the articles), with articles with two (23.8%) and four (19.7%) authors also very frequently occurring. The share of single-authored articles drops significantly to 10.9%, which is nearly the same as articles with five authors (9.7%). Articles with six and even seven authors are no longer a rarity. This period can be characterized as the fully developed period of research collaboration.

It is noteworthy that over the whole publication period of JOA and SS, articles with more than 10 authors are rare, amounting to less than 0.4% of the total. The article with most authors published in SS is entitled 'Nanotechnologies, engineered nanomaterials and occupational health and safety', with no less than 22 authors. Such hyper-collaboration articles are however a rarity in *Safety Science*.

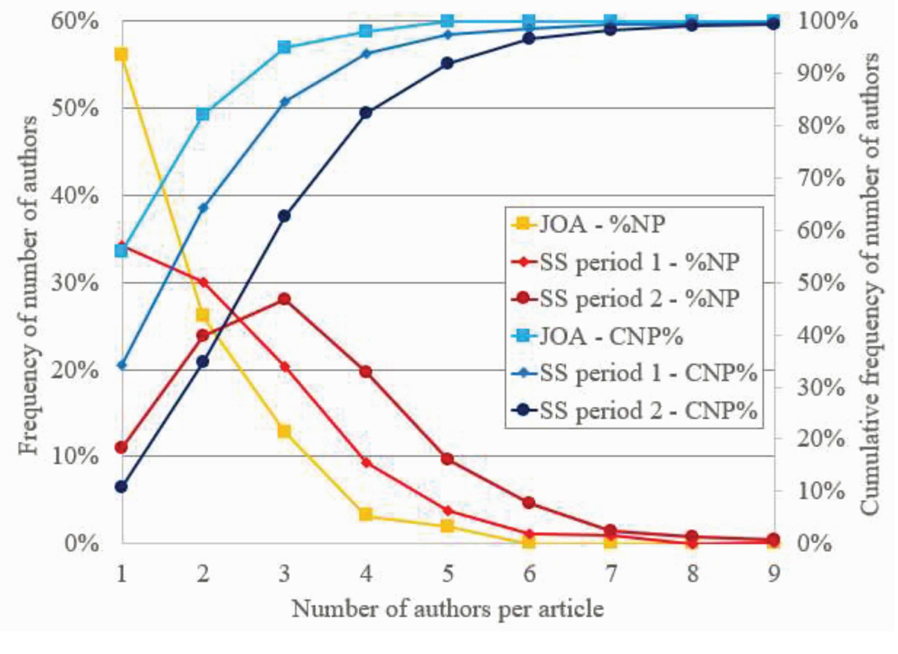


Figure 4 Number of authors of the papers published in JOA (1976-1990) and SS (1991-2019)

3.2 Evolution of scale of author networks in Safety Science

This Section investigates the scale of collaboration in *Safety Science*, focusing on RQ2 of the introduction. Hence, the overall network structure of all publications published in the time periods identified in Section 2.1 is mapped, and high-level metrics of the networks are calculated to assess their structure. Here, the number of nodes and collaboration links, diameter, largest connected network, average degree, density, and average clustering coefficient is used to obtain insights.

Fig. 5 shows the evolution of the scale of the author networks in Safety Science for the three identified time periods. The size of the networks is graphically represented so that the area of the networks is proportionate to the number of authors in the network, to give a visual cue concerning the overall growth of the research volume. In the networks, the node sizes correspond to the number of articles authored by a given author. The thickness of the links between nodes indicates the collaboration strength between the two authors. The colors highlight various connected author networks within the complete network. Together, these visual cues give a qualitative impression of the level of collaboration. The figure confirms the very significantly increased research volume in the three periods, as found in Fig. 1. It also provides an initial appreciation of the increasing interconnectedness of the *Safety Science* research community. According to Fig. 5a, the collaboration network in Period I is composed of many isolated authors, with a limited number of small and relatively remote clusters. In Fig. 5b, a development to somewhat larger and more numerous collaboration clusters can be identified for Period II. Finally, Fig. 5c shows numerous collaboration clusters, some of which are very large. Nevertheless, it is apparent that in Period III, there is a rather large number of small collaboration networks associated with authors with few articles published. This suggests that while a set of core *Safety Science* research collaboration clusters can be identified, often associated with prolific authors as seen by the node sizes, the journal also contains many articles authored by researchers with a possibly weak link to the safety science research community.

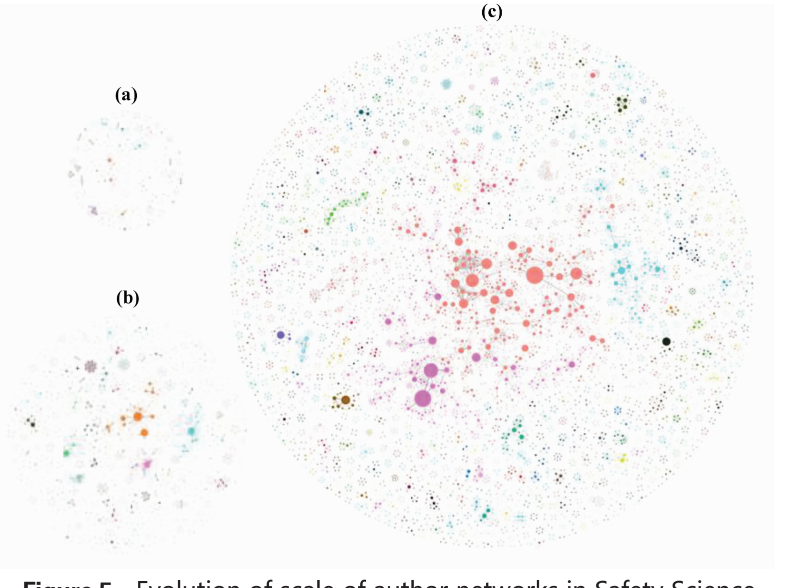


Figure 5 Evolution of scale of author networks in Safety Science
(a) Period I: JOA (1976-1990), (b) Period II: SS1 (1991-2007),(c) Period III: SS2 (2008-2019)

Table 2 shows the calculated metrics serving as indicators of collaboration scale of the networks shown in Fig. 5. Clearly, the number of authors and the number of collaboration links has increased very strongly from Period I to Period III. In Period I, there are only 344 authors, whereas in Period III, there are 6595. Similarly, in Period I, there are 278 collaboration links, corresponding to the low level of co-authored publications as found in Fig. 3 and Fig. 4. In contrast, in Period III, there are 12801 collaboration links, indicating a high level of co-authorships.

The number of collaborators of an author in a collaboration is known as the 'degree' of the node associated with the author (Ding et al., 2014). The average degree is calculated by counting the average number of links per author. It provides information about the interconnectedness between authors. With higher average degrees, the network is tighter and the collaboration scale is higher (Yin et al., 2006). From Table 2, it is evident that the average degree has increased from 1.616 in Period I to 3.882 in Period III.

The diameter of a network is the longest graph distance between any two of its authors (Bastian et al., 2009). Because collaboration links imply a social connection, networks with longer diameters are associated with more socially integrated research communities (Ding et al., 2014). Table 2 shows that the diameter in Period I was only 5, whereas in Period III it has increased to 26. This shows that the *Safety Science* research community, or at least a core cluster of authors, has become increasingly socially connected. A similar observation can be made based on the size of the largest connected network, which has grown from a mere 14 in Period I to 1449 in Period III. While naturally not all authors in a connected network know one another, an increased size of significantly connected networks is generally taken to indicate a more socially connected research community (Zhao & Zhao, 2016).

The network density corresponds to the average number of connections an author in the network has compared to the total possible connections. It thus provides insights into how likely an author, on average, is connected to a random other author in the network, which can be seen as a proxy of how likely he is to know that author (Ding et al., 2014). From Table 2, it is seen that the density decreases from 0.005 in Period I to 0.001 in Period III. This indicates that while there are larger network clusters in *Safety Science*, the author community overall has become less socially integrated.

Finally, the average clustering coefficient, a measure of how strongly nodes cluster together, is calculated for the networks of each period. This measure indicates how strongly an author is embedded in his neighborhood (Bastian et al., 2009). The results of Table 2 indicate that the average clustering coefficient has remained rather stable across the three periods. The values around 0.9 suggest that the *Safety Science* community mostly consists of comparatively more active central researchers who collaborate with other researchers, whereas these other researchers do not in turn collaborate with one another. Considering the results of Fig. 5, this suggests that the *Safety Science* community consists of several core researchers who ensure the continuity of the research domain, who work in changing co-author constellations.

Table 2 Metrics of collaboration scale and authors collaboration network over time

Metric	Period I: JOA 1976–1990	Period II: SS1 1991–2007	Period III: SS2 2008–2019
Number of nodes/authors	344	1377	6595
Number of edges/collaboration links	278	1762	12801

Metric	Period I: JOA 1976–1990	Period II: SS1 1991–2007	Period III: SS2 2008–2019
Average degree	1.616	2.559	3.882
Diameter	5	9	26
Size of largest connected network	14	90	1449
Density	0.005	0.002	0.001
Average clustering coefficient	0.891	0.913	0.911

3.3 Evolution of highly productive authors in Safety Science

The findings from Section 3.1 and Section 3.2 indicate that the *Safety Science* research community has become increasingly interconnected over time, with growing clusters of research networks around several highly productive authors and increasing prevalence and scale of collaborative publishing. In this Section, these highly productive authors are identified, providing an answer to RQ3.

To determine the most productive authors in each period, a heuristic is sought, balancing the increase in productivity of particular authors and the overall increase in the research volume. According to RQ3 and RQ4, the collaboration networks of these authors are determined and further interpreted in terms of the key research themes. Hence, a heuristic is needed, which ensures that sufficient clusters are shown to enable an interpretation, while limiting the number of clusters to keep the analysis manageable.

Table 3 gives the results of an analysis of how many authors there are with a given number of publications in the three different time periods. These results are obtained through a simple count of the integrated JOA-SS dataset obtained as explained in Section 2.1. Full counting is applied, i.e., publications are counted to an author regardless of his position in the author list. It is seen that in Period I, an author with four or more articles can be considered a prolific author, publishing more than 98.26% of the other authors. In Period II, an author with six or more publications can be considered a highly productive author, involved in more publications than 99.20% of the other authors. In Period III, the goalpost shifts again, with involvement in nine or more publications being a reasonable judgment to be considered a highly productive author. These numbers are selected based in part on the observation that for a category with fewer associated publications, the number of authors increases relatively sharply.

Table 3 Number of authors with given number of publications in different time periods

	Period I: JOA (1976–1990)			Period II: SS1 (1991–2007)			Period III: SS2 (2008–2019)		
NP	NA	NA%	NAC%	NA	NA%	NAC%	NA	NA%	NAC%
1	276	80.23	80.23	1137	82.57	82.57	5242	79.48	79.48
2	40	11.63	91.86	135	9.80	92.37	791	11.99	91.48
3	19	5.52	97.38	66	4.79	97.17	290	4.40	95.88
4	3	0.87	98.26	14	1.02	98.18	112	1.70	97.57
5	0	0.00	98.26	11	0.80	98.98	56	0.85	98.42
6	3	0.87	99.13	3	0.22	99.20	29	0.44	98.86
7	2	0.58	99.71	3	0.22	99.42	23	0.35	99.21

Period I: JOA (1976–1990)				Period II: SS1 (1991–2007)			Period III: SS2 (2008–2019)		
NP	NA	NA%	NAC%	NA	NA%	NAC%	NA	NA%	NAC%
8	0	0	99.71	1	0.07	99.49	17	0.26	99.47
9	1	0.29	100	0	0.00	99.49	6	0.09	99.56
10				3	0.22	99.71	4	0.06	99.62
11				0	0	99.71	6	0.09	99.71
12				1	0.07	99.78	3	0.05	99.76
13				1	0.07	99.85	4	0.06	99.82
14				1	0.07	99.93	5	0.08	99.89
⩾15				1	0.07	100	7	0.11	100

Note:NP=Number of publications | NA=Number of authors | NA%=Percentage of number of authors| NAC%=Percentage of Cumulative number of authors

Table 4 lists the most productive authors of *Safety Science* for the three considered periods identified in Fig. 1, based on the results of Table 3. It also shows the average number of articles these authors published annually over the entire considered time periods, and the percentage of all articles published in which the researcher was (co-) author, for each period.

As may be expected, due to the relatively long-time span of each period, there are relatively few authors who are highly productive across multiple periods. Andrew Hale, Emeritus professor of *Safety Science* at Delft University of Technology (the Netherlands), who served as editor of *Safety Science* for 20 years, is the only scholar who has achieved this. He is also the most active contributor in Period II. Torbjorn Rundmo, professor at the Department of Psychology of the Norwegian University of Science and Technology (Norway), was the second most prolific author in Period II, and still a top contributor to *Safety Science* in Period III. Neville Stanton, professor of human factors in transport at the University of Southampton (United Kingdom), was a highly productive author in Period II, and has become the second-most active contributor in Period III. In Period I, Dr. Jorma Saari of the Finnish Institute of Occupational Health (Finland) was the most contributing author to *Journal of Occupational Accidents.* In Period III, Genserik Reniers, professor in the safety of hazardous materials at Delft University of Technology (the Netherlands), with appointments at the KU Leuven and at the University of Antwerp (Belgium), is the most active author.

3.4 Key research topics of collaboration networks of core researchers

In this Section, the collaboration networks of the core researchers in *Safety Science* are identified, and their key research topics are determined, answering RQ4. This is done by extracting the connected networks in which the highly productive authors listed in Table 4 are located, using the Gephi software (Bastian et al., 2009). Subsequently, the highest-cited articles of the core authors are obtained from the integrated JOA-SS dataset for each period, from which key influential research topics of the collaboration networks are determined. The key co-authors of the core researchers of Table 4 are identified as those with the highest number of co-authored articles with the core researchers.

3.4.1 Period I: JOA (1976–1990)

The collaboration networks of the core researchers of Period I, listed in Table 4, are shown in Fig. 6. The node sizes represent the number of publications by the respective author, while

Table 4 Most productive authors in the development periods of Safety Science

Period I: JOA (1976–1990)				Period II: SS1 (1991–2007)				Period III: SS2 (2008–2019)							
Author name	NP	NPY	%TP	Author name	NP	NPY	%TP	Author name	NP	NPY	%TP	Author name	NP	NPY	%TP
Saari, J.	9	0.60	2.87	Hale, A.R. ■	17	1.00	2.10	Reniers, G.	28	2.33		Griffin, M.A.	11	0.92	
Kjellén, U.	7	0.47	2.23	Rundmo, T.†	14	0.82	1.73	Stanton, N.A.†	27	2.25		Hasle, P.	11	0.92	
Manning, D.P.	7	0.47	2.23	Chang, W.R.	13	0.76	1.61	Salmon, P.M.	23	1.92		Khakzad, N.	11	0.92	
Ayoub, M.A.	6	0.40	1.91	Laflamme, L.	12	0.71	1.48	Hale, A.R. ■	21	1.75		Li, Q.	11	0.92	
Hale, A.R. ■	6	0.40	1.91	Kirwan, B.	10	0.59	1.24	Khan, F.	19	1.58		Nordfjaern, T.	11	0.92	
Proctor, T.D.	6	0.40	1.91	Larsson, T.J.	10	0.59	1.24	Ale, B.J.M.	17	1.42		Utne, I.B.	11	0.92	
Harris, G.W.	4	0.27	1.27	Manning, D.P.	10	0.59	1.24	Swuste, P. †	15	1.25		Celik, M.	10	0.83	
H?kkinen, K.	4	0.27	1.27	Beroggi, G.E.G.	8	0.47	0.99	Aven, T.	14	1.17		Hallowell, M.R.	10	0.83	
McQuaid, J.	4	0.27	1.27	Davies, J.C.	7	0.41	0.87	Chinniah, Y.	14	1.17		Rollenhagen, C.	10	0.83	
				Flin, R.	7	0.41	0.87	Dekker, S.	14	1.17		Wybo, J.–L.	10	0.83	
				Swuste, P. †	7	0.41	0.87	Mearns, K.	14	1.17		Aneziris, O.A.	9	0.75	
				Hoyes, T.W.	6	0.35	0.74	van Gulijk, C.	14	1.17		Cozzani, V.	9	0.75	
				Kjellén, U.	6	0.35	0.74	Boustras, G.	13	1.08		Kines, P.	9	0.75	
				Stanton, N.A. †	6	0.35	0.74	Le Coze, J.C.	13	1.08		Leka, S.	9	0.75	
								Newman, S.	13	1.08		Nielsen, K.J.	9	0.75	
								Rundmo, T. †	13	1.08		Wu, C.	9	0.75	
								Goerlandt, F.	12	1.00					
								Guldenmund, F.	12	1.00					
								Maiti, J.	12	1.00					

Notes: NP = Number of publications I NPY = Number of publications (co–) authored per year of the periods indicated in Fig. 1 I %TP = Percentage of total number of articles published in period in which author is (co–author), total number of publications as shown in Fig. 1 I ■ = Authors appearing as high–ranked in all three periods I†= Authors appearing as high–ranked in two periods the link thickness indicates the collaboration strength. It is seen that there are only a few core safety science researchers in this period, namely nine. These have small collaboration networks where most co-authors only are involved in one joint publication. There are only two network clusters in which core researchers appear together, but in only one (cluster #5) have these in fact co-authored an article. As also found in Fig. 5, the small networks of these core researchers are isolated islands, and the networks are mostly loosely clustered. This confirms the findings of Section 3.1 and Section 3.2 that in Period I, there is no significant research collaboration in the safety science community.

The key collaborators, impactful research topics, and highly cited papers of these core researchers are shown in Table 5. It is seen that, in line with the original scope and aims of JOA to focus on occupational accidents, influential focus research topics include various technical aspects of work safety. Important networks associated with this line of work concern those of Manning D.P. (cluster #2), Proctor T.D. (#5), and Harris G.W. (#5), who focused on slip and fall accidents, and slip resistance; that of Häkkinen G.W. (#6) focused on safety of portable ladders and crane accidents, while Ayoub M.A. (#3) worked on safety of manual lifting, and McQuaid J. (#7) on water sprays and gas plumes. However, the most influential authors from this period focused on more human and organizational aspects of safety. The network around Saari J. (#1) focused on analysis of work accidents, the disturbed information flow between humans and environments in accident occurrence, and motivational strategies and positive feedback in organizational safety programs. Kjellén U. (#1) focused on deviations in investigating and controlling workplace accidents, and on safety information systems. Finally, Hale A.R. (#4) investigated safety training and the development and use of safety rules in behavioral safety strategies.

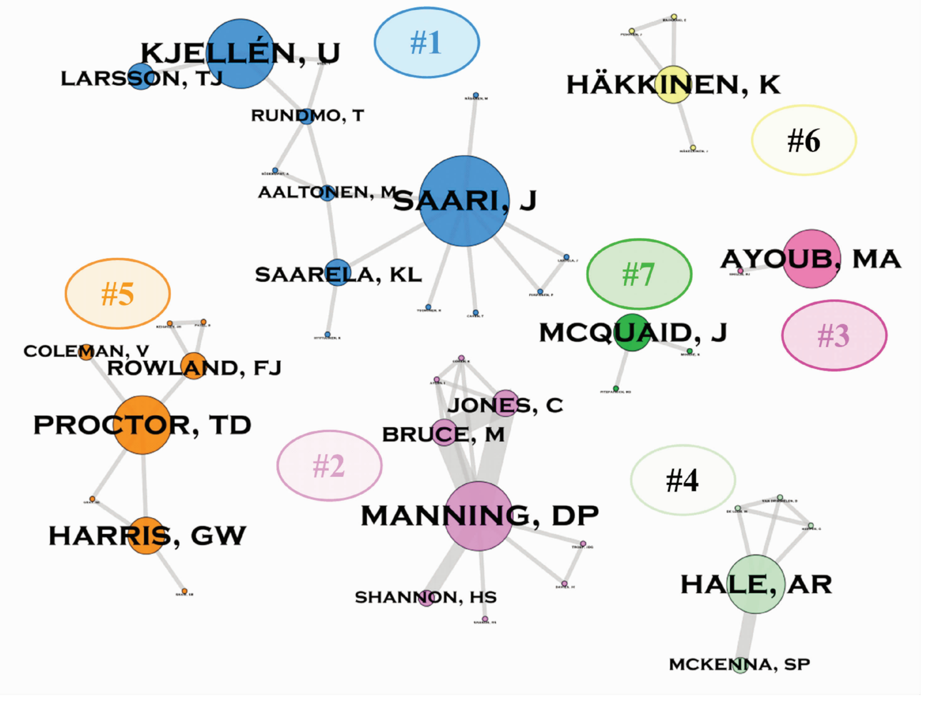


Figure 6 Collaboration networks of core Safety Science researchers, Period I: JOA (1976-1990)

Table 5 Core Safety Science researchers, Period I: JOA (1976-1990) Key co-authors, research topics, and highly cited papers

Author name	C–ID	Key co–authors	Research topics	Highly cited papers
Saari, J.	#1	Saarela, K.L.; Aaltonen, M.	Safety activities; behavioral safety; positive feedback; accident analysis	(Saarela et al., 1989; Tuominen and Saari, 1982; Näsänen and Saari, 1987; Saari, 1990)
Kjellén, U.	#1	Larsson, T.J.; Rundmo, T.	Deviations; safety information systems; accident investigation	(Kjellén and Larsson, 1981; Kjellén, 1982; 1984)
Manning, D.P.	#2	Bruce, M.; Jones, C.	Slipping accidents; underfoot accidents; slip–resistance;	(Bruce et al., 1986; Manning et al. 1988; Manning et al., 1990)
Ayoub, M.A.	#3	Smillie R.J.	Manual lifting; accident causation; simulation modeling	(Smillie and Ayoub, 1976; Ayoub 1982)
Hale, A.R.	#4	McKenna, S.P.	Behavioral safety; safety training, first aid training	(Hale, 1990; 1984; Mckenna and Hale, 1981)
Proctor, T.D.	#5	Harris, G.W.; Rowland, F.J.	Slipping, tripping, and falling; industrial helmets	(Proctor, 1982; Proctor and Coleman, 1988)
Harris G.W.	#5	Proctor, T.D.	Slip resistance; eye protectors	(Harris, 1987; Harris and Shaw, 1988)
Häkkinen, K.	#6	Pesonen, J.; Rajamäki, E.	Portable ladders; crane accidents	(Häkkinen, 1978; Häkkinen et al., 1988)
McQuaid, J.	#7	Fitzpatrick, R.D.; Moodie, K.	Water sprays; gas plumes	(McQuaid and Fitzpatrick, 1983; McQuaid and Moodie, 1983)

Note:C-ID = Cluster identification as per Fig. 6

3.4.2 Period II: SS1 (1991–2007)

The collaboration networks of the core researchers of Period II, listed in Table 4, are shown in Fig. 7, with a similar graphical interpretation as for Fig. 6. It is seen that with 14 core *Safety Science* researchers, there are somewhat more core researchers in this period than in the previous one. Moreover, there are larger connected network clusters, particularly cluster #1 of Fig. 1, which contains eight core researchers. Several of the core researchers of this cluster have furthermore co-authored articles, in some cases several. The networks of the other highly productive authors are also larger than the networks observed in Fig. 6 for Period I. This indicates that research collaboration intensified in this period, with some highly productive authors having steady co-authorship relations in their local network, for instance, in clusters #2, #3 and #5. Nevertheless, the networks of the other highly productive authors are not connected, indicating that this is a transition phase in the development of collaborative research in *Safety Science*.

The key collaborators, impactful research topics, and highly cited papers of these core researchers are shown in Table 6. It is seen that overall, there is continued influential research on selected technical work safety-related issues, in particular, slip resistance and slip and fall accidents (cluster #2 and #5) and aspects of occupational and road transport accidents (cluster #1, #3 and #4). However, there is a clear shift in the importance of psychological aspects of safety, e.g., risk perception, situational awareness, risk homeostasis, and human-centered design (cluster #1), and of organizational and social mechanisms such as safety climate and culture, safety management, the role of safety rules, leadership and safety professionals (cluster #1). A final cluster focusing on emergency response and group decision making furthermore marks a new impactful research direction within *Safety Science* (cluster #6).

While it is apparent that there is increased collaborative research centered around the core researchers, as indicated above, there is no significant research collaboration between core researchers working on similar topics, with many networks unconnected even if these focus on similar research themes. Only in cluster #1 there is an emerging international collaboration between core *Safety Science* researchers. Within this cluster, Hale A.R. is a central actor, collaborating with Swuste P. on safety rules, with Kirwan B. and Kjellén U. on design safety and with Kirwan B. on safety management systems, with Rundmo T. on managers' attitudes towards safety and accident prevention. In cluster #5, there is an intense national collaboration between Manning D.P. and Davies J.C. on missed-step accidents and accident information models.

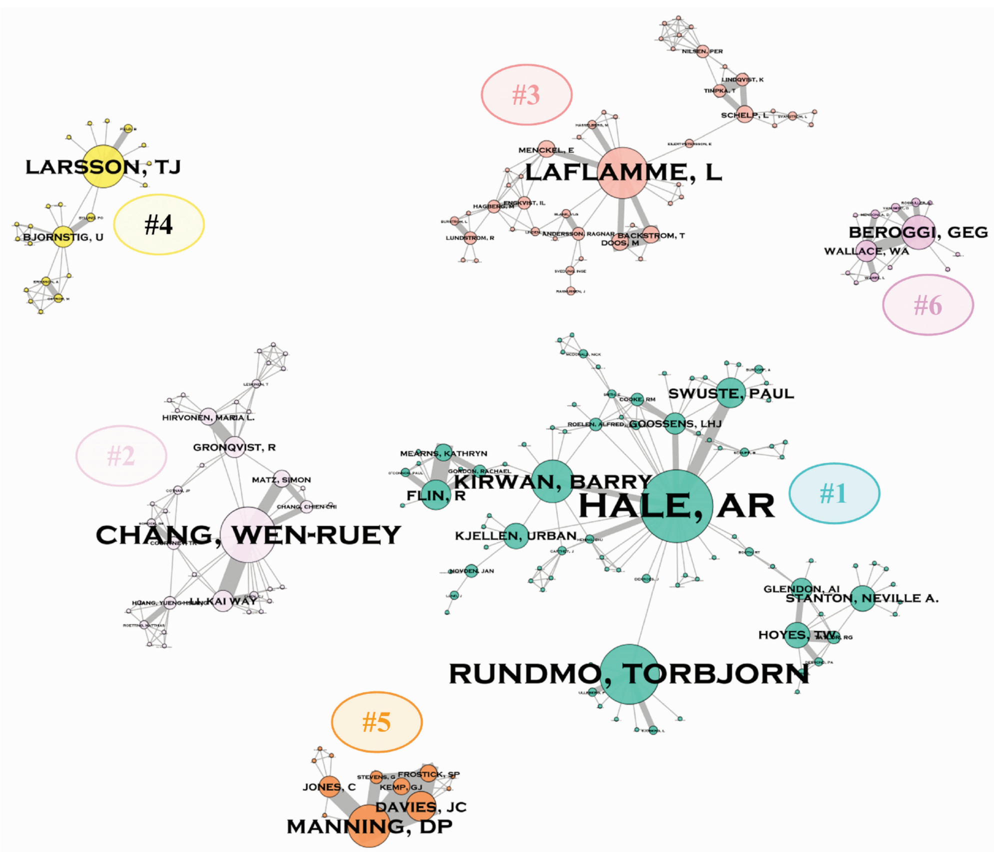


Figure 7 Collaboration networks of core Safety Science researchers, Period II: SS1 (1991-2007)

Table 6 Core Safety Science researchers, Period II: SS1 (1991-2007) Key co-authors, research topics, and highly cited papers

Author name	C–ID	Key co–authors	Research topics	Highly cited papers
Hale, A.R.	#1	Kirwan, B.; Swuste, P.; Goossens, L.	Managers' attitudes; safety rules; safety management systems; design safety; safety professionals	(Hale, 1995; Hale et al., 1997; Hale and Swuste, 1998; Rundmo & Hale, 2003; Hale et al., 2007)
Rundmo, T.	#1	Sjoberg, L.; Ulleberg, P.	Risky driving behaviour, risk perception; personality and gender; safety climate; managers' attitudes	(Ulleberg & Rundmo, 2003; Rundmo, 1996; Oltedal & Rundmo, 2006; Rundmo, 2000; Rundmo & Hale, 2003)
Chang, W.R.	#2	Li, K.W.; Matz, S.	Slipperiness measurement; slip criterion; dynamic friction; friction measurement	(Li et al., 2004; Chang, 2002; 1998; Li et al., 2007)
Laflamme, L.	#3	Backstrom, R.; Döös, M.	Occupational accidents; aging; accident patterns; car safety; young adult; gender	(Laflamme et al., 1991; Laflamme & Menckel, 1995; Laflamme et al., 2005; Monárrez –Espino et al., 2006)
Kirwan, B.	#1	Hale, A.R.; Kjellén, U.	HAZOP; safety culture; safety management systems; design safety; human reliability	(Kennedy & Kirwan, 1998; Hale et al., 1997; Hale et al., 2007; Kirwan, 1997)
Larsson, T.J.	#4	Field B.; Bjornstig U.	Occupational injury; road trauma; construction industry; forklift trucks	(Larsson & Rechnitzer, 1994; Bylund et al., 1997; Larsson & Field, 2002)
Manning, D.P.	#5	Davies, J.C.; Jones, J.; Kemp, G.; Stevens, G.	Slip resistance; footwear; missed–step accidents; accident information model	(Manning & Jones, 1994; Manning et al., 1991; Davies et al., 2001)
Beroggi, G.E. G.	#6	Wallace, W.A.; Rosmuller N.; van Gendt, D.	Emergency response; group decision making; conflict resolution	(Timmermans & Beroggi, 2000; Rosmuller & Beroggi, 2004; Mendonça et al., 2006)
Davies, J.C.	#5	Manning, D.P.; Frostick, S.P.; Kemp, G.J.	Missed–step accidents; accident information model	(Davies et al., 2001; Davies & Manning, 1994)
Flin, R.	#1	Mearns, K.	Safety climate; safety management; safety culture; safety leadership	(Flin et al., 2000; O'Dea & Flin, 2001; Mearns et al., 2003; Flin, 2007)
Swuste, P.	#1	Hale, A.R.	Safety rules; safety adviser; organizational change	(Hale & Swuste, 1998; Swuste & Arnoldy, 2003)
Hoyes, T.W.	#1	Desmond, P.A.; Glendon, A.I.; Taylor R.G.	Risk homeostasis theory; behavioral adjustment; workload; intrinsic risk	(Desmond & Hoyes, 1996; Hoyes et al., 1996)
Kjellén, U.	#1	Hale, A.R.; Kirwan, B.	Design safety; human –centered design; barrier	(Hale et al., 2007; Kjellén, 2007)
Stanton, N.A.	#1		Safety culture; situational awareness	(Glendon, 2000; Stanton et al., 2001)

Note: C-ID = Cluster identification as per Fig. 7

3.4.3 Period III: SS2 (2008–2019)

The collaboration networks of the core *Safety Science* researchers of Period III, listed in Table 4, are shown in Fig. 8 and Fig. 9, with similar graphical interpretations as for Fig. 6. It is seen that with 35 core researchers, there are significantly more highly productive researchers in this period than in the two previous ones. Moreover, these are grouped in 20 collaboration clusters, of which 16 are connected to one another in a very large, connected network. This indicates that national and international research collaboration between core Safety Science researchers has become much more common and developed. For instance, in cluster #1, Reniers G. acts as a central actor in collaborations with other highly active researchers and their local groups, such as Khakzad N., Cozzani V., Khan F. and Wu C. In cluster #2, there is a strong collaboration between Stanton N.A. and Salmon P; in cluster #3 between Hale A.R., Ale B.J.M., and Aneziris O.N.; and in cluster #4 between Swuste P., van Gulijk C. and Guldenmund F, and between Boustras G., Wybo J.-L., and Guldenmund F. Furthermore, there are various collaborations between core researchers across clusters, e.g., between Reniers G. (#1) and Ale B.J.M. (#3), Reniers G. (#1) and Goerlandt F. (#12), and Salmon P. (#2) and Newnam S. (#10) and Hasle P. (#15) and Kines P. (#20). There are also several moderately and many low productive *Safety Science* authors bridging core researcher clusters, e.g., Zwetsloot G. and Zwaard W. linking clusters #4 and #20, or Yan X.P. and Haugen S. linking clusters #12 and #17.

Apart from the increased scale of collaboration across the overall *Safety Science*

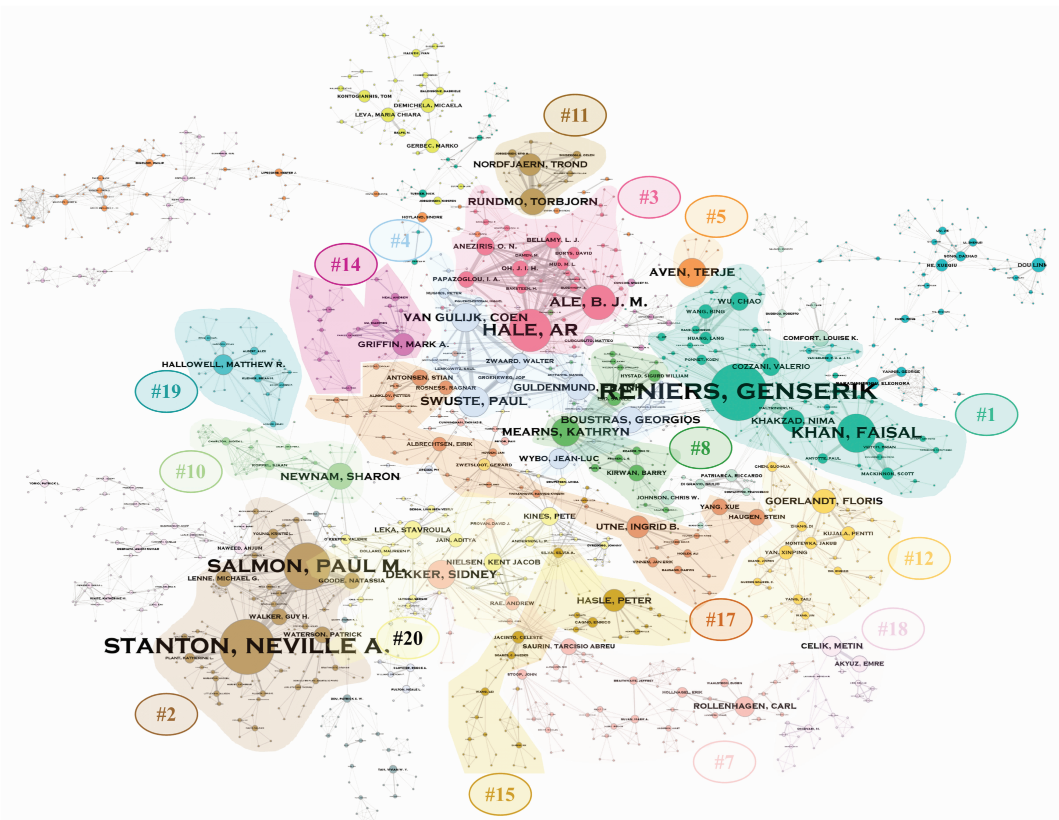


Figure 8 Collaboration networks of core *Safety Science* researchers, Period III: SS2 (2008-2019),Largest connected network containing most core researchers of Table 6

community, as observed in Section 3.2, it is seen that the networks of the highly productive authors are also significantly larger than the networks observed in Fig. 6 and Fig. 7 for Periods I and II. This indicates that research collaboration has much intensified in this period, with highly productive authors commonly having steady co-authorship relations in their local network, along with a range of occasional collaborators. It also suggests that there is an increasingly strongly linked *Safety Science* research community. Nevertheless, there are some highly productive authors with their own significant research networks, who are not connected to the other core researchers.

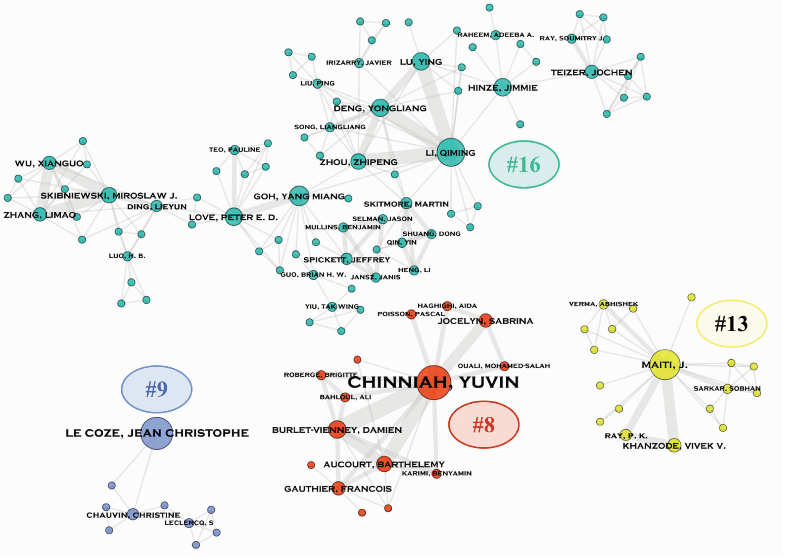


Figure 9 Collaboration networks of core Safety Science researchers, Period III: SS2 (2008-2019),Networks of other core researchers of Table 6: Chinniah, Y.; Le Coze, J.C.; Maiti, J.; and Li, Q.

The key collaborators, impactful research topics, and highly cited papers of these core researchers are shown in Table 7. It is seen that overall, compared to the previous periods, there is less influential research on technical aspects of work safety and occupational risk. Instead, there is a further increased attention to psychological aspects of safety, e.g., human performance in road transport (cluster #2), risk perception (#8 and #11), and psychological risk management (#20). It is apparent that the most influential work addresses organizational aspects of safety, with topics such as safety management (#3, #4, and #16), safety climate and culture (#1, #3, #4, #8, #11, and #20), safety rules and procedures (#3, #14, and #7), and safety indicators (#17, #19) important research areas.

Compared to the previous periods, in Period III there is also an increased focus on using models and methods for safety decision making, with topics such as Bayesian networks (#1, #4, #17) and risk assessment (#1, #3, #6, #13, #18) attracting considerable attention. Furthermore, there are more clusters with work addressing the conceptual and theoretical basis of safety-related terms and accident causation mechanisms, e.g., related to risk (#5), safety metaphors and models (#4, #9), and complexity (#2, #7). Another apparent trend is the diversification and intensification of research oriented towards specific industry clusters. For instance, there are important clusters focusing primarily or extensively on safety in the chemical and process industries (#1, #3, #4), road transport (#2, #10, #11), construction (#16, #20), maritime transport (#12, #17, #18), oil and gas (#1, #17), and micro-firms and SMEs (#4, #15). Finally, several new topics are influential in the research networks of highly productive authors, for instance bibliometrics (#4), validation and evaluation research (#12, #20), safety education (#4), terrorism (#1), and big data (#1).

Table 7 Core Safety Science researchers, Period III: SS2 (2008-2019) Key co-authors, research topics, and highly cited papers

Author name	Cluster	Key co–authors	Research topics	Highly cited papers
Reniers, G.	#1	Khakzad, N.; Cozzani, V.; Goerlandt, F.; Ponnet, K.	Pedestrian evacuation; risk diagrams; safety culture; occupational accidents; process industry; quantitative risk analysis	(Vermuyten et al., 2016; Goerlandt & Reniers, 2016; van Nunen et al., 2018; Goerlandt et al., 2017; Wang et al., 2018)
Stanton, N.A.	#2	Salmon, P.M.; Walker, G.H.; Plant, K.L.	Human error; road safety; vehicle automation; systems perspective; complexity	(Stanton & Salmon, 2009; Salmon et al., 2012; Plant & Stanton, 2012; Banks et al., 2014; Salmon et al., 2010)
Salmon, P.M.	#2	Goode, N.; Stanton, N.A.; Lenne, M.G.; Walker, G.H.	Accident analysis methods; systems perspective; human error; road safety; driver distraction; driver training	(Salmon et al., 2012; Young & Salmon, 2012; Stanton & Salmon, 2009; Salmon et al., 2012; Beanland et al., 2013)
Hale, A.R.	#3	Baksteen, H.; Bellamy, L.J.; Papazoglou, I.A.	Safety rules; safety procedures; safety management; safety culture; occupational risk; safety performance indicators	(Hale & Borys, 2013a; 2013b; Hale et al., 2010; Ale et al., 2008; Hale, 2009)
Khan, F.	#1	MacKinnon, S.; Veitch, B.; Khakzad, N.	Bayesian network; offshore safety; process safety; dynamic risk analysis; human reliability assessment; risk–based design	(Khakzad et al., 2013; Abimbola et al., 2015; Villa et al., 2016; Musharraf et al., 2013; Rathnayaka et al., 2014)
Ale, B.J.M.	#3	Slater, D.; Reniers, G.	Occupational risk; continuous improvement; chemical industry; ALARP; CBA; PCDs	(Ale et al., 2008; Reniers et al., 2009; Ale et al., 2015; Ale et al., 2015)
Swuste, P.	#4	Zwaard, W.; van Gulijk, C.; Groeneweg, J.; Lemkowitz, S.	Safety management; safety metaphors; safety theories; occupational health and safety; safety education	(Swuste et al., 2010; Arezes & Swuste, 2012; Swuste et al., 2012; Swuste et al., 2016)
Aven, T.	#5	–	Risk perspective; risk concept; ontology; uncertainty; probability; black swan	(Steen & Aven, 2011; Aven et al., 2011; Aven & Reniers, 2013; Aven, 2013)
Chinniah, Y.	#6	Burlet –Venney, D.; Aucourt, B.	Machinery safety; risk assessment; confined spaces; occupational safety	(Chinniah, 2015; Burlet –Vienney et al., 2015a; 2015b)
Dekker, S.	#7	Henriqson, E.; Rae, A.J.	Complexity; systems perspective; human error; bureaucratization; criminalization	(Dekker et al., 2011; Larsson et al., 2010; Dekker, 2014; Dekker, 2011)
Mearns, K.	#8	Kirwan, B.; Eid, J.	Safety climate; perceived risk; national culture; safety behavior; situation awareness; organizational support	(Meliά et al., 2008; Mearns & Yule, 2009; Sheddon et al., 2013; Mearns & Reader, 2008)

Author name	Cluster	Key co–authors	Research topics	Highly cited papers
van Gulijk, C.	#4	Swuste, P.; Zwaard, W.	Safety metaphors; safety theories; occupational safety; Bayesian network; process plant	(Swuste et al., 2010; Swuste et al., 2014; Ale et al., 2014)
Boustras, G.	#4	Dimopoulos, C.; Hadjimanolisa A.	Health and safety; micro –firms; safety climate; bibliometrics	(Hadjimanolis & Boustras, 2013; Boustras et al., 2015; Merigó et al., 2019)
Le Coze, J.C.	#9	–	Complexity; safety models; learning from accidents; disasters; socio–technical view	(Le Coze, 2013a; 2013b; 2015)
Newnam, S.	#10	Koppel, S.; Watson, B.	Driving safety; occupational driving; behaviour, age; volunteers	(Newnam & Watson, 2011b; 2011a; Newnam et al., 2014)
Rundmo, T.	#11	Nordfjaern, T.; Jorgensen, S.H.; Simsekoglu, O.	Safety climate; safety culture; traffic safety; risk perception; transport mode	(Tharaldsen et al., 2008; Lund & Rundmo, 2009; Rundmo et al., 2011)
Goerlandt, F.	#12	Reniers, G.; Kujala P.; Montekwa J.	Maritime transportation; maritime safety; uncertainty; validation	(Goerlandt & Montewka, 2015; Goerlandt & Kujala, 2014; Goerlandt & Reniers, 2016; Goerlandt et al., 2017)
Guldenmund, F.	#4	Groeneweg, J.; Swuste, P.	Safety interventions; safety culture; safety management systems; migrant workers	(Hale et al., 2010; Swuste et al., 2012; Guldenmund et al., 2013)
Maiti, J.	#13	Khanzode, W.; Ray, P.K.	Occupational accident; risk assessment; hazard identification; risk–based maintenance	(Khanzode et al., 2012; Arunraj & Maiti 2010; Khanzode et al., 2011)
Griffin, M.A.	#14	Hu, X.W.	Safety leadership; safety compliance; safety rules	(Griffin & Hu 2013; Hu et al., 2016)
Hasle, P.	#15	Hohnen, P.	Accident prevention; audit; OHSM; SME	(Hasle et al., 2009; Hohnen & Hasle, 2011)
Khakzad, N.	#1	Reniers, G.; Khan, F.	Bayesian network; risk analysis; offshore safety	(Khakzad et al., 2013; Abimbola et al., 2015)
Li, Q.	#16	Deng, Y.L.; Lu, Y.; Zhou, Z.P.	Safety management; construction; near miss	(Wu et al., 2010; Zhou et al., 2015)
Nordfjaern, T.	#11	Rundmo, T.; Simsekoglu, O.	Risk perception; transport mode; driver behaviour	(Rundmo et al., 2011; Nordfjaern et al., 2010)
Utne, I.B.	#17	Holmen, I.M.; McGuinness, E.	Safety indicators; maritime transport; bayesian network; oil and gas	(?ien et al., 2011; Akhtar & Utne, 2014; Skogdalen et al., 2011)
Celik, M.	#18	Akyuz, E.	Shipping accident; marine engineering; fault tree; FMEA; human error; risk assessment	(Celik et al., 2010; Cicek & Celik, 2013; Akyuz & Celik, 2014)
Hallowell, M. R.	#19	Hardison, D.; Albert, A.	Safety indicator; construction; supervisor competency	(Hardison et al., 2014; Lingard et al., 2017)

Author name	Cluster	Key co–authors	Research topics	Highly cited papers
Rollenhagen, C.	#7	Hollnagel, E.; Lundberg, J.; Wahlstrom, B.	Accident investigation; accident model; experience feedback	(Lundberg et al., 2009; Lindberg et al., 2010)
Wybo, J.–L.	#4	Zwetsloot, G.I.J.M.; Van Wassenhove W.	Zero accident vision; safety culture; HSE professionals	(Zwetsloot et al., 2013; Wybo & Van Wassenhove, 2016)
Aneziris, O.A.	#3	Papazoglou, I.A.; Bellamy, L.J.; Oh, J.	Occupational risk; Quantitative risk analysis; fall from height; crane	(Aneziris et al., 2008; Aneziris et al., 2008)
Cozzani, V.	#1	Reniers, G.; Landucci, G.	Dynamic risk analysis; process industry; terrorist attack	(Villa et al., 2016; Argenti et al., 2015)
Kines, P.	#20	Nielsen, K.J.; Pedersen, L.M.; Zwetsloot, G.I.J.M.	Construction; SME; injury; zero accident vision	(Hasle et al., 2009; Zwetsloot et al., 2013)
Leka, S.	#20	Jain, A.; Iavicoli, S.	Psychological risk; work stress; occupational health and safety	(Leka et al., 2011; Leka et al., 2011)
Nielsen, K.J.	#20	Kines, P.; Pedersen, L.M.	Evaluation design; safety intervention; safety climate	(Nielsen et al., 2008; Pedersen et al., 2012)
Wu, C.	#1	Wang, B.; Huang, L.	Work safety; five –year plan; big data	(Wang et al., 2018; Ouyang et al., 2018)

Note: C-ID = Cluster identification as per Fig. 8 and Fig. 9

4 Discussion

4.1 Interpretation of the results

The findings of Section 3.1 clearly show that research in *Safety Science* has become increasingly collaborative in nature over time, with the prevalence and scale of collaboration rapidly increasing. As shown in Section 3.2, this leads to a remarkedly altered structure of the *Safety Science* research community: whereas initially research was performed predominantly by single authors or in small, disconnected clusters, in the current period the research community is characterized by large, connected clusters around highly productive researchers. Nevertheless, the macro-level analysis of Fig. 5 and Table 2 also indicates that despite the intensified research collaborations and developments towards increasingly interconnected research clusters, most researchers publishing in *Safety Science* author very few articles and are not connected to the collaboration networks of the core researchers. The decrease in the overall network density and the stability of the average clustering coefficient at a low level furthermore indicates that comparatively few researchers publish in *Safety Science* for extended periods of time. This may be due to the plethora of safety-related journals available to publish in, see e.g., Reniers and Anthone (2012) and Li and Hale (2015; 2016). Another likely reason is that the core researchers are mostly academics with faculty positions, whereas many of their changing collaborators in their local clusters are probably graduate students who do not publish (significantly) after graduating. A final possible explanation for this is that there are in fact relatively few researchers who focus on safety concepts, theories, methods and tools per se, whereas many occasional authors may be academically active in other domains of science (engineering, psychology, sociology, etc.) and publish only in *Safety Science* because of a passing interest in safety, e.g., in context of a specific engineering design or organizational study.

Considering the key influential research topics of the core researchers, the results of Section 3.4 show that *Safety Science* has become a platform for a wide range of multidisciplinary research topics, in which collaborative research in networks clustered around core researchers has become the norm. This suggests that there is an increasingly well-established core *Safety Science* research community, although there is a high diversity in the topics addressed. Furthermore, the results of Table 7 confirm earlier findings from Li and Hale (2016) and Merigó et al.(2019) that the safety research community is characterized by a series of co-existing conceptual approaches and theories about safety, and associated methods. For instance, core researchers such as Aven T. in clusters #5, Khan F. and Khakzad N. (#1), and Celik M. (#18) focus on (model-based) risk assessment to support safety decision making. Other researchers focus on safety management systems as organizational tools to monitor and manage safety, e.g., Hale A.R. (cluster #3), Swuste P. and Guldenmund (#4), and Li Q. (#16). Other clusters focus on safety climate and culture, e.g., Rundmo T. (cluster #11) and Guldenmund F. (#4), or base safety thinking on systems- or complexity theories, e.g., Stanton N.A. (cluster #2), Dekker S. (#7), and Le Coze J.C. (#9).

The observation that there are multiple coexisting safety concepts, theories, models, and methods is of course hardly surprising, as this has in fact been a key influential research topic by authors such as Swuste P. and van Gulijk C. (cluster #4) and Le Coze J.C. (#9). It is also evident by historic accounts of *safety science* as a research field (Dekker, 2019), and has been raised as a point of confusion and uncertainty in industrial contexts (Guillaume et al., 2018). However, considering the results of Fig. 5 and Table 2, which indicate that there are very many occasional authors in *Safety Science* with no collaboration connection to the larger research networks and little integration in the safety research community, it gives rise to the question to what extent such occasional authors are aware of this conceptual, theoretical, and methodological diversity in the research domain, and of their implications. It may be a fruitful avenue of future research to investigate this to better understand to what extent *safety science* can be considered a well-established discipline. Such knowledge can also be useful to design educational programs, or to serve as a basis for reflection for editors and reviewers when considering articles for publication in *Safety Science*.

Finally, while the increase in the prevalence and scale of research collaboration has not earlier been investigated in *Safety Science*, similar trends observed in other disciplines and research communities (Abrahams et al., 2019; Fan et al., 2020; Zhao & Zhao, 2016; Franceschet, 2011) suggest that is a wider phenomenon in academia, which probably can be at least partially explained by increased publication pressure in especially university research environments across disciplines (Haven et al., 2019). Scientific collaboration has been associated with several advantages, such as knowledge sharing, cross-fertilization of ideas, coping with the complexities of multi- and interdisciplinary work, and increased visibility (Franceschet & Constantini, 2010). However, publication pressures and the associated increases in research outputs can also incentivize perverse multiplication of authorship and low quality of research (Binswanger, 2014; Sarewitz, 2016). The results of Section 3 merely aim to describe and document the fast-increasing research productivity and prevalence and scale of collaboration, and hence are not meant to provide conclusions on whether increased collaboration and networking is desirable or not, or if it is beneficial for the development of *safety science*. However, being mindful of a recent discussion by Rae et al. (2020), who asserts that safety research is stagnating and is at risk of becoming a degenerate research program, the current research findings can serve as a basis to support hypotheses and future research to assess whether increased collaboration and productivity is beneficial to the development of *safety science,* and if so, for whom and under which conditions.

Finally, it is however noteworthy that several core researchers in Fig. 8 and Fig. 9 have small collaboration networks, e.g., Aven T. (cluster #5) and Le Coze J.-C. (#9), indicating that collaboration is not a prerequisite for academic impact. This is also observed e.g., in the process safety research domain, where one of the pioneers and most influential scholars, Dr. Trevor Kletz, authored by far most of his work alone (Li et al., 2020b).

4.2 Study limitations

As with any study, the current work has several limitations which warrant some caution about the results. First, the division of the publication timeline of JOA and SS in the three periods as in Fig. 1 is a choice by the authors. While the overall publication trends can be taken as a good basis for a temporal division, and while the selected periods clearly have distinct features, other choices of time periods may be feasible and may lead to somewhat different results. Second, other heuristics could be used to identify the core authors, e.g., based on the number of citations rather than on the number of publications or based on the number of years in which the authors published in *Safety Science*. The ranking of authors by the identified periods may also lead to some core authors not being shown, as their work may be split across two of these periods. The ranking of core authors should therefore be taken with some caution. Hence, their ranking in Table 4 should primarily be seen as a means of elucidating the developments of collaboration networks and associated key influential focus topics, rather than an appreciation of the importance of individual researchers or an endorsement of their work. Finally, the focus in this work is only on safety publications in JOA and SS. Considering that there are many other safety-related journals (Reniers & Anthone, 2012; Li & Hale, 2015), in which many of the core authors publish as well, the relative rank of authors and the structure of their collaboration networks may look somewhat different if those publication outlets are accounted for as well. Such analyses may be worthwhile in future research, where also the extent of international research collaboration between different networks, and other aspects, e.g., related to research quality or industrial impact, may be interesting to further investigate.

5 Conclusions

In this article, the development of research collaboration in *Safety Science* (including its predecessor Journal of Occupational Accidents) has been investigated. Observing three distinct stages in the overall publication trends in the journal, the articles are analyzed using scientometric analysis and visualization techniques.

A first finding is that both the prevalence and scale of collaborative publishing have increased significantly over time. Whereas initially, most articles (ca. 75%) were written by a single author, there has been a gradual increase in the prevalence of collaborative work, with in recent years, only ca. 5% of the articles being authored by a single researcher. In the three development periods, there is also a clear trend to larger numbers of co-authors: initially, only ca. 18% of the articles has three or more authors, whereas in the recent period, this number has risen to 65%, with multi-author publications having become the de facto norm.

The second main finding is that the collaboration networks in *Safety Science* have become increasingly large and more interconnected over time, indicating the growth of a core research community. Nevertheless, the local network structure remained largely similar, in that many highly productive researchers collaborate with changing authors over time. There is also a trend towards increased collaborative work between core researchers, leading to large, connected networks. However, even in the current period of high interconnectedness and clustering, there are many authors who have no collaboration links to other author clusters in *Safety Science*. This may indicate that while there is a core safety research community, other scholars have a more passing interest in safety.

In terms of the key research themes addressed by the core researchers and their networks, it is observed that initially, there was a strong focus on technical aspects of work safety, and to some extent on human and organizational aspects of safety. Over time, this emphasis has gradually shifted towards psychological phenomena and social mechanisms in safety. In the recent period, this trend continues, with additionally an increased focus on safety and risk models and methods, the conceptual and theoretical basis of safety-related terms and accident causation mechanisms, and emergence of influential research clusters focusing on particular safety aspects of specific industries.

Apart from providing high-level insights into the development of the *safety science* domain, the findings can also serve as a basis for future scholarship investigating the coherence and maturity of *safety science* as a discipline, and for investigating the benefits and drawbacks of increased productivity and collaboration.

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