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Mapping process safety: A retrospective scientometric analysis of three process safety related journals (1999–2018)

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ABSTRACT

Over the last decades, process safety has been an important area of academic inquiry, aiming to build knowledge which can contribute to reduce the occurrence of industrial accidents in the process and chemical industries, or to mitigate their consequences. Knowledge in this interdisciplinary research domain is created using applied science, engineering, organizational, and social science approaches. This article provides a retrospective overview of the process safety research field, through the lens of three major journals contributing to the development of this knowledge domain: *Journal of Loss Prevention in the Process Industries*, *Process Safety and Environmental Protection*, and *Process Safety Progress*. An analysis of the articles in these journals, published between 1999 and 2018, provides insights in the structure, developments, trends, and highly influential works in this research domain, while revealing differences and similarities between these three core process safety journals. General publication trends, the geographic distribution of leading knowledge producers (countries/regions and institutions), their collaboration and temporal evolution patterns, topic clusters and emerging trends, and highly cited sources and articles, are identified and discussed.

1. Introduction

The chemical and process industries, like many other human activities, have been affected by large-scale accidents. Due to the presence of hazardous substances, these accidents often result in very high casualty rates and significant environmental and economic consequences (Kletz, 2009). Consequently, process safety and loss prevention has been an active area of industrial, regulatory, and academic work.

The first issue of the *Journal of Loss Prevention in the Process Industries* was published in 1988. Over the subsequent decades, it has become one of the leading outlets for the communication of knowledge about process-related injuries and damages, with a focus on chemical and process plant safety. It publishes applied research based on the physics and engineering of fires, explosions, and toxic releases, aimed at preventing losses. As the practice of loss prevention is highly interdisciplinary, the journal also addresses the related social, policy, and organizational aspects, including incident investigation, process safety and risk management, process safety culture, human and organizational factors, process security risk assessment and management, process safety education and training, and process safety decision-making and economic issues.

The primary aim of this article is to present a retrospective overview of the process safety research domain. Such retrospective analyses have recently been made for other leading journals in other areas of academic activity, for instance for operations research (Laengle et al., 2017), safety science (Merigó et al., 2019), and transportation research (Modak et al., 2019). Such high-level overviews are of interest to academics and practitioners working in the topic domain, contextualize their own work, and serve to obtain insights in important knowledge domains and emerging trends. Retrospective overviews can also be instrumental to early career academics, to identify the main authors and highly-cited articles in a research domain, which can expedite their familiarization with a research domain (Li et al., 2020). Especially when comparing several journals, comparative overviews can furthermore be instrumental for prospective authors to select a suitable journal to which to submit their work (Li and Hale, 2016).

Several literature review articles have been published on particular topics within process safety and loss prevention, to provide detailed insights in the progress and knowledge gaps of specific research topics, for instance concerning liquefied natural gas risk analysis (Animah and Shafiee, 2019) emergency evacuation in chemicals-concentrated areas (Dou et al., 2019), inherent process safety indicators (Jafari et al., 2018),

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process safety education (Mkpat et al., 2018), boiling liquid expanding vapor explosions (BLEVEs) (Eckhoff, 2014), and risk assessment methods at work sites (Marhavilas et al., 2011).

Notwithstanding the great value of such narrative reviews to the development of specific research domains, the methods applied in classical review articles are not well-suited for providing a high-level overview of a journal as a knowledge carrier, primarily because of the large numbers of published articles, their very labor-intensive nature of classical review methods (Grant and Booth, 2009). Classical review methods are also limited as they do not easily translate to a visual representation of a research domain (Li et al., 2020), whereas visualizations are important for guiding human cognition, interpretation, and memory (Simoff et al., 2008).

Scientometric methods present a suitable alternative approach to obtain high-level insights in a research domain. By applying mathematical methods to quantitative metrics and information about journal articles, patterns, developments, and trends can be readily visualized and patterns, developments, and trends conveniently identified and interpreted (Li et al., 2020). Consequently, scientometric analyses have been performed to obtain high-level overviews of the structure and patterns of journals (Laengle et al., 2017; Merigó et al., 2019; Modak et al., 2019). The techniques have also been used to analyze broad knowledge domains relevant to process safety, for instance domino effects in the process industries (Li et al., 2017) and pool fires (Liu et al., 2019).

Considering the above, the primary aim of this article is to present a retrospective overview of the process safety research domain, identifying publication trends, highly impactful contributions, authors, and geographic regions, dominant clusters of research, emerging research topics, and knowledge exchange patterns between leading academic journals. Three highly impactful journals in the process safety research domain are selected as a basis for this analysis: *Journal of Loss Prevention in the Process Industries* (JLPPI), *Process Safety and Environmental Protection* (PSEP), and *Process Safety Progress* (PSP). These are selected to allow broad insights in the structure, main themes, and influential works in the process safety domain, and to enable a comparative analysis of the development patterns and trends of these leading journals. To allow a retrospective comparative analysis which allows insights in recent developments, considering that these journals have different years of publication of their first issue, a 20-year period of analysis is chosen: from 1999 up to and including 2018.

The journals are selected based on the experience of especially the third author with these journals and supported by their high journal impact factor. Journals impact factor (JIF) represent the average number of citations to a journal in the past two years (Beatty et al., 2012), and it has become an influential and wildly used indicator to measure the quality and influence of a journal in a research domain. The annual trends of the JIF of these journals are displayed in Fig. 1, covering the period 1999–2018. A descriptive statistical analysis of the JIFs using boxplots is shown as well, giving further insights. The boxplots contain information about the medians and lower 25% and 75% quantiles using the boxes and show outliers and minima and maxima values using the whiskers extending from the central boxes. It is seen that in the period from 1999-to 2008, the three journals have quite similar JIFs, whereas after 2008 the JIF gap between each journal becomes increasingly obvious. The JIF of PSEP increased rapidly, reaching 4.384 in 2018. The figure illustrates that PSEP has become the most influential process safety journal in terms of JIF. JLPPI has seen a gradually increasing JIF since about 2008, whereas the JIF of PSP has remained relatively stable or at least has only slowly increased over this time period. By exploring topic clusters and areas of recent high research activity using scientometric methods, some underlying reasons underlying these different evolutions in JIF scores can be explored.

The remainder of this article is organized as follows. In Section 2, the data source and data extraction process are described, and a brief overview is given of the applied scientometric methods and analysis process. The results of the scientometric analysis are presented and discussed in Section 3. Overall publication trends, geographic distribution of and collaborations between main contributing countries/regions and institutions, topic clusters and their temporal evolution, knowledge communication between journals, and highly influential articles, are identified and interpreted. Section 4 concludes.

2. Data and method

2.1. Data source

The bibliographic data of the three selected process safety journals were retrieved from Web of Science Core Collection (WOSCC). In the 'Advanced search' interface of WOSCC, a search strategy based on the publication name (source, SO) was applied: SO = (Journal of Loss Prevention in The Process Industries), for the sub-dataset 'SCI-EXPANDED', and with the timespan set from 1999 to 2018. Article, review, and proceedings papers are more the important document types as carriers of scientific knowledge, with these three types accounting for 85% of the contributions in each analyzed journal. In the current work, these three types are selected as the final sample data for a depth analysis. Articles in the other analyzed journals are obtained in a similar way, by changing the journal title (i.e. SO = (Process Safety Progress) and SO = (Process Safety and Environmental Protection)). The detailed data retrieval

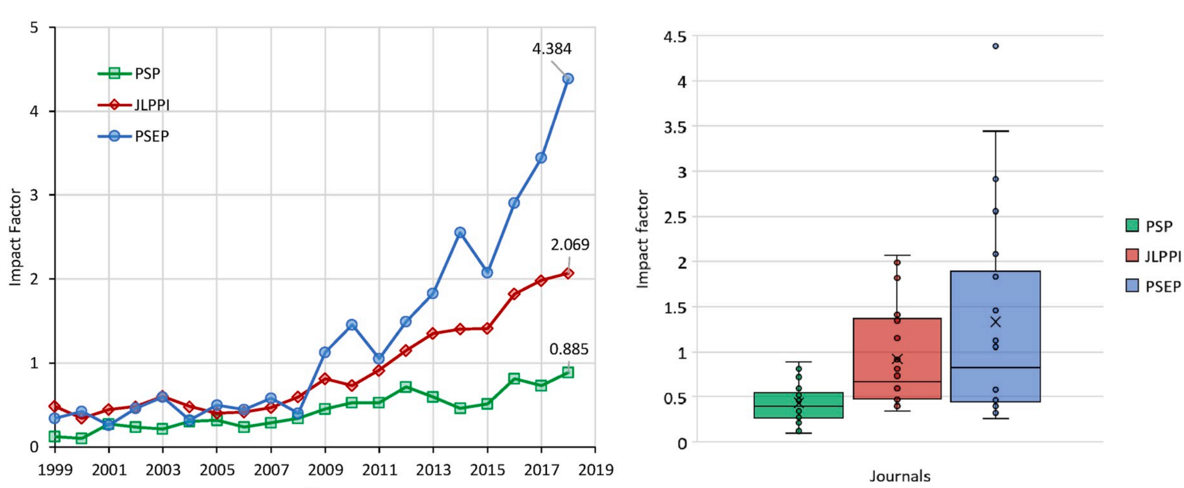


Fig. 1. Annual trends of Journal impact factor of JLPPI, PSEP and PSP,JIF-data obtained from journal citation report.

strategy and its results are show in Fig. 2. The data extraction was performed on 10-9-2019. Detailed summary information of each journal is listed in Table 1. There are 2405 records from JLPPI, which ranks first among these journals, followed by PSEP (n = 1889), and PSP (n = 1001). Both JLPPI and PSEP are published in England and release 6 vol per year (see Fig. 3).

A note is in place on the selection of the data sources. As stated in the introduction, the focus of the current research is to provide a retrospective overview of the process safety research domain. This is performed through three core process safety journals. A direct search of keywords related to process safety in WOSCC was attempted, but as this leads to a very high number of irrelevant articles (due to words such as 'safety' and 'process' being very generic), the choice is made to focus on the journals JLPPI, PSEP, and PSP. Other journals which also publish on closely related topics, such as *Reliability Engineering and System Safety*, *Safety Science*, and *Journal of Hazardous Materials*, are not accounted for. This is either because they include a lot of work on hazards and safety in other industrial domains, or because they focus on quite specific aspects of process safety. Based on the analysis results of the intellectual basis of the selected journals (Section 3.4), it is found that the selected journals are closely related to each other and separated from other journals. This supports the restriction to the analysis of the three selected journals.

2.2. Methods and analysis process

In the current work, bibliometric analysis methods are applied, and the bibliometric mapping tool VOSviewer is used to visually represent the scientometric analysis results, facilitating visual interpretations. Bibliometric analysis methods originate from information and library sciences, and can be characterized as "the application of mathematics and statistical methods to books and other media of communication" (Mingers and Leydesdorff, 2015). With the advent of the data science age, bibliometric methods have been combined with network analysis and data visualization techniques, which lead to the new research area known as 'bibliometric/scientometric mapping'. This research domain focuses on developing quantitative methods based on mathematical analyses and statistics, and tools for visually representing scientific literature based on bibliographic data.

Recently, bibliometric mapping analysis has become of interest not only inside the scientific communities of information and library sciences, but also in other scientific communities. There currently are more than 30 free used tools already developed for bibliometric mapping (Li, 2017), with VOSviewer being one of the most widely used tools among these. VOSviewer is short for 'Visualization of Similarity', which was developed by van Eck and Waltman (2010). The tool has serval functions for bibliometric mapping, including collaboration analysis (e.g. authors, institutions, and countries/regions), topics analysis (e.g. keywords or terms), and citations-based analysis (e.g. bibliographic coupling and co-citations). The reader is referred to (Li et al., 2020)for an overview of the main concepts underlying these analyses.

Several papers have already applied VOSviewer for bibliometric mapping in safety related topics, e.g. output distributions and topic maps of safety related journals (Li and Hale, 2016), safety journals identification (Li and Hale, 2015), safety culture (van Nunen et al., 2018), construction safety (Akram et al., 2019; Jin et al., 2019), process safety (Amin et al., 2019; Yang et al., 2020), domino effects (Li et al., 2017), laboratory safety in universities (Yang et al., 2019), and road safety research (Zou et al., 2018). (Li et al., 2020)provide a more comprehensive overview of bibliometric analyses on safety related

Table 1
Number of records obtained from Web of Science.

Journals Title	NP	NARP	P (%)	PF	PL	JIF 2018	TC
JLPPI[a]	2490	2405	96.59%	6	England	2.069	30,599
PSEP[b]	2007	1889	94.12%	6	England	4.384	25,082
PSP[c]	1153	1001	86.82%	4	USA	0.885	5052

Notes: JLPPI = Journal of Loss Prevention in the Process Industries | PSEP = Process Safety and Environmental Protection | PSP = Process Safety Progress | JIF = Journal impact factor | NP = Number of papers | NARP = Number of articles, review and proceedings papers |P (%) = NARP/NP | PF = Publication frequency (journal issues/year) | PL = Publisher location | TC = Total number of citations of the journal.

[a] Homepage of Journal of Loss Prevention in the Process Industries. https://www.sciencedirect.com/journal/journal-of-loss-prevention-in-the-process-industries.

[b] Homepage of Process Safety and Environmental Protection. https://www.journals.elsevier.com/process-safety-and-environmental-protection/.

[c] Homepage of Process Safety Progress. https://www.wiley.com/en-us/Process+Safety+Progress-p-9780471669821.

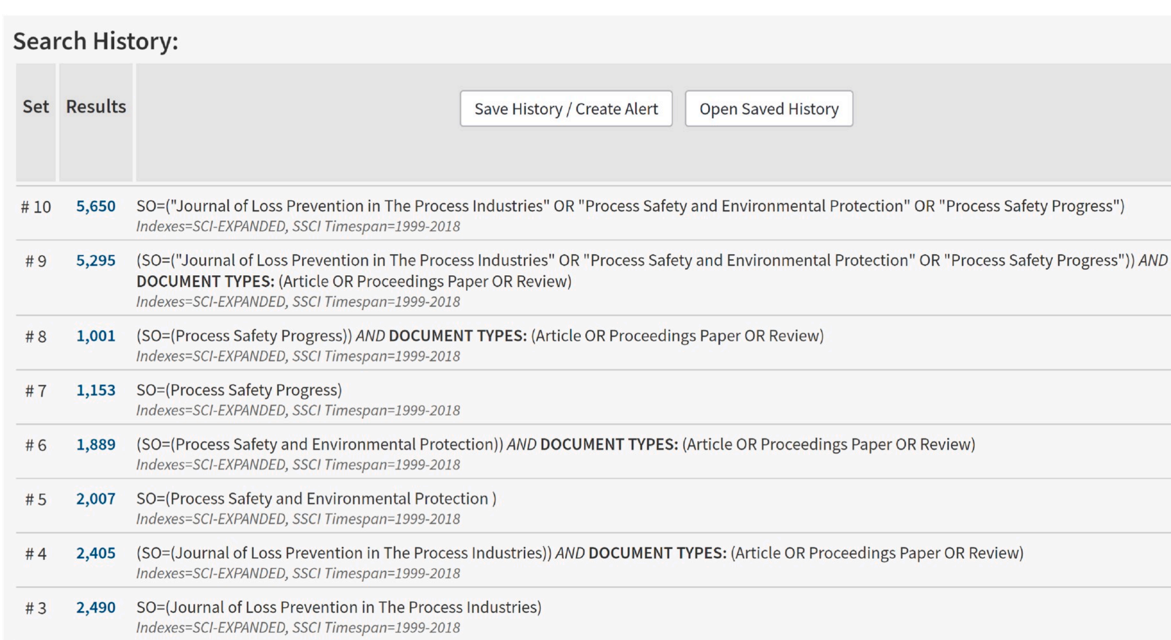


Fig. 2. Data retrieval strategies in Web of Science.

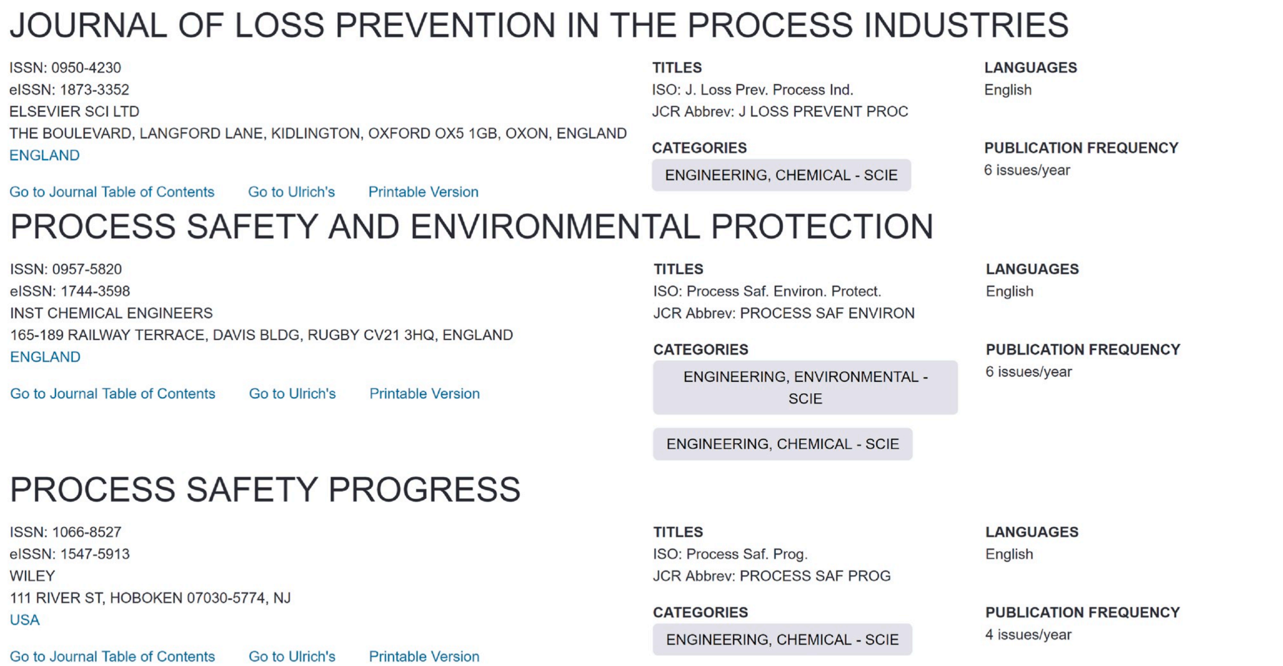


Fig. 3. Journals information from Journal Citation Reports.

topics.

In bibliometric analyses, scientific journals are considered as knowledge carriers, whereas publications are understood as knowledge units, which focus on a particular topic and are connected to the literature. The analysis of a specific journal or a group of journals is helpful to understand the evolution of the structure, main themes, and influential works in the research area. Several articles have performed bibliometric analyses on specific journals, e.g. *Transportation Research* journals (Modak et al., 2019), The *Journal of Mechanism and Machine Theory* (Flores, 2019), *Computers & Industrial Engineering* (Cancino et al., 2017), and *European Journal of Operational Research* (Laengle et al., 2017). In the safety research area, Li et al. (2013) have made a preliminary knowledge map of safety science based on the *Safety Science* journal. More recently, Merigó et al. (2019) have used various bibliometric methods to analyze forty years of publications in *Safety Science*, including publications trends, leading producers (authors, institutions, and countries/regions), and highly-cited papers and references.

Some scientometric analyses which focus on the development of journals as knowledge carriers in a given research domain focus on only one journal, e.g. Cancino et al. (2017), Merigó et al. (2019) and Flores (2019). Other analyses focus on identifying differences between journals focusing on closely related topics, e.g. Li and Hale (2016). The present work aligns with the latter approach, focusing on identifying similarities and differences between the developments of three core process related journals. In the current research, three journals focusing on process safety (i.e. JLPPI, PSEP, and PSP) are selected for analysis, as outlined in the introduction.

A flowchart describing the analysis process for these process safety related journals is shown in Fig. 4. The general workflow of scientometrics mapping research includes data retrieval, pre-processing including data cleaning and disambiguation (harmonizing data fields where different records may e.g. use a different abbreviation of a name), network extraction, normalization, mapping, analysis, visualization, interpretation by an analyst to obtain some insights from the results, see (Li et al., 2020) for a description of these steps. In the current work, four main analyses are performed: publication trends, geographic distribution of leading producers, terms co-occurrence clusters, and intellectual base analysis. These are briefly described next:

3. Results

3.1. Publication trends

The publication trend in terms of the number of published papers is a quantitative indicator for the scientific activity and attention in a certain domain. Fig. 5 and Table 2 show the annual number of articles published in each of the three journals, where in Fig. 5 the horizontal axis shows the publication year, and the vertical axis the number of papers has published in each year. The results indicate an increasing trend for each journal, and especially for JLPPI and PSEP. This increase in annual output clearly shows the growth of the scientific production in process safety domain.

The marked increase in output of JLPPI began in 2009, when the annual number of published articles exceeded 100 papers, reaching over 150 papers per year from 2013 onwards. The annual output of PSEP shows a very significant change during the considered time period. There are about 50 papers per year before 2014, with 2014 marking a very sharp increasing trend, suddenly jumping to 98 in that year, and reaching 343 papers in 2018. Apart from a growing interest and activity in process safety research, this indicates that PSEP has changed the editorial policies, leading to a higher volume of papers being submitted and/or accepted in the journal. Compared to JLPPI and PSEP, the output of PSP has changed less significantly during the observed timespan, with a slowly increasing trend and an average output of nearly 50 papers per year, with the lowest standard deviation among the three journals. The cumulative number of publications of JLPPI ($R^2 = 0.9399$) and PSEP ($R^2 = 0.9339$) follow an exponential growth, whereas PSP is better characterized by a linear growth model ($R^2 = 0.9905$).

3.2. Geographic distribution of and collaboration between leading knowledge producers

In this Section, the geographic distribution of the published articles during the period 1999 to 2018 in the three analyzed process safety journals is analyzed, taking countries/regions and institutions as levels of analysis. Collaboration networks and temporal evolutions are identified as well.

Fig. 6 shows the countries/regions collaboration network in process

Fig. 4. Flowchart of process safety documents analysis.

(1) Publication trends of process safety: the annual outputs of process safety publications in the analyzed journals are shown and selected descriptive statistics are analyzed. This result provides a high-level overview of the research activity of process safety in the 20 years from 1999 to 2018.

(2) Leading institutions and countries/regions in the collaboration network: the highly productive institutions and countries/regions are analyzed to show where the key knowledge producers originate from, what collaborations between these exist, and how these have evolved over time. This analysis is based on the visualization of similarities approach by van Eck and Waltman (2010), using VOSviewer.

(3) Terms co-occurrence clusters: terms are noun phrases, which are extracted from titles and abstracts of the 5295 papers using a text mining and clustering algorithm described in van Eck et al. (2010a). Terms are labeled as 'co-occurring' if they appear together in the same paper. The terms co-occurrence network is clustered based on the co-occurrence strength using network clustering method in VOSviewer.

(4) Intellectual base analysis: cited articles can be seen as the intellectual base of a research field, on which future knowledge seeking activities build (Persson, 1994). In the present work, a two-level intellectual base analysis is performed (cited sources and cited articles) is analyzed, using journals and references co-citation analysis as implemented in VOSviewer.

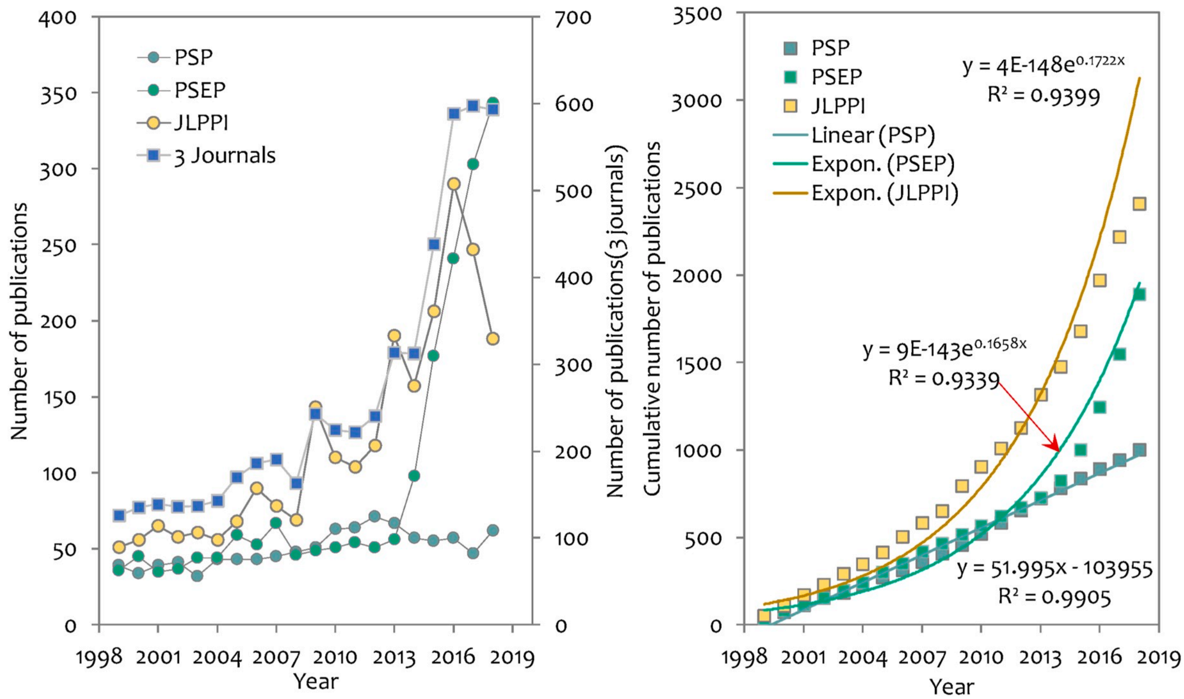


Fig. 5. Annual number of publications and cumulative number of publications:trends for JLPPI, PSEP, and PSP from 1999 to 2018.

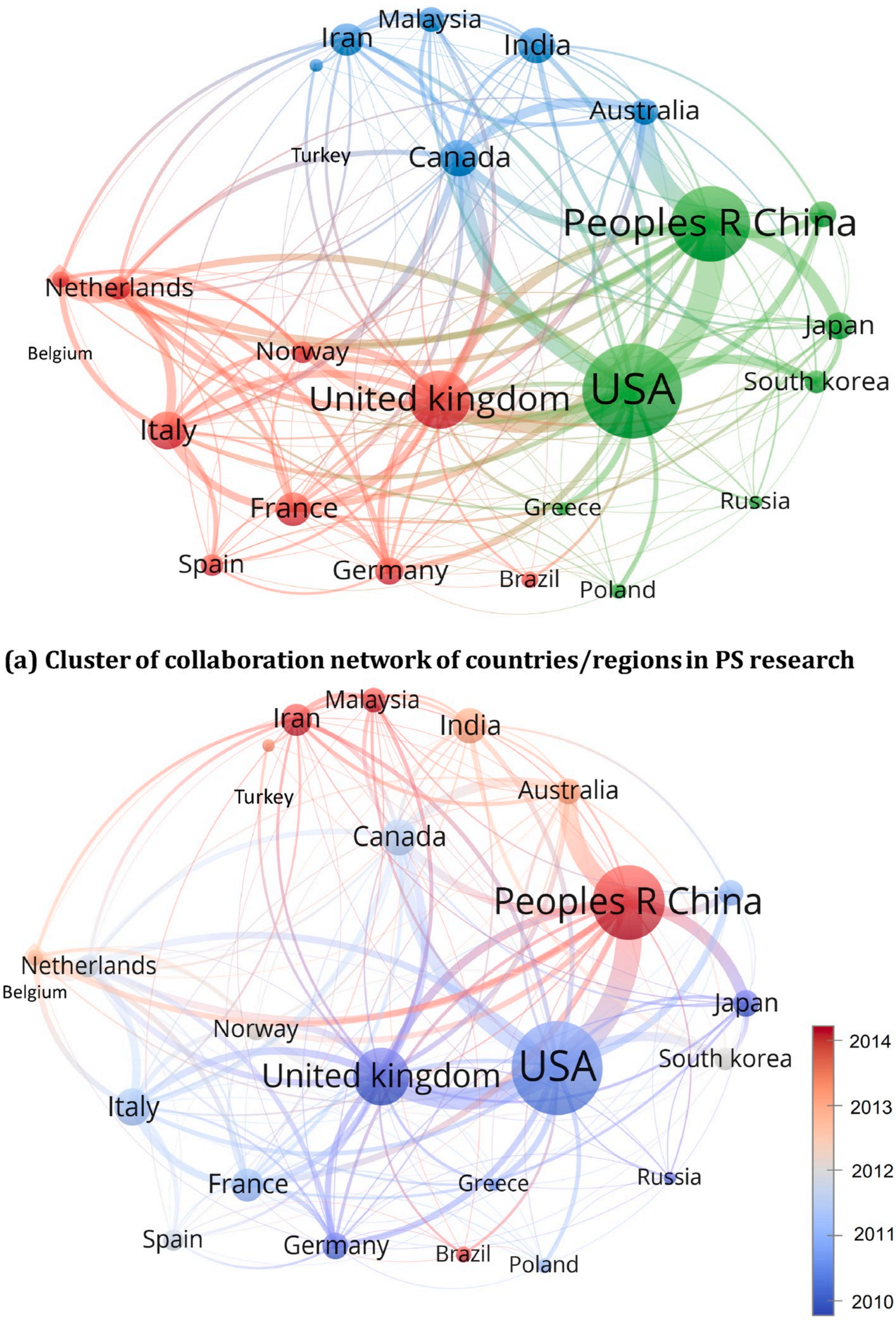
Table 2
Annual outputs and cumulative number of publications of each journal from 1999 to 2018.

Years	JLPPI				PSEP				PSP			
	NP	CNP	% sum	% cum	NP	CNP	% sum	% cum	NP	CNP	% sum	% cum
1999	51	51	2.12%	2.12%	36	36	1.91%	1.91%	39	39	3.90%	3.90%
2000	56	107	2.33%	4.45%	45	81	2.38%	4.29%	34	73	3.40%	7.29%
2001	65	172	2.70%	7.15%	35	116	1.85%	6.14%	39	112	3.90%	11.19%
2002	58	230	2.41%	9.56%	37	153	1.96%	8.10%	41	153	4.10%	15.28%
2003	61	291	2.54%	12.10%	44	197	2.33%	10.43%	32	185	3.20%	18.48%
2004	56	347	2.33%	14.43%	44	241	2.33%	12.76%	43	228	4.30%	22.78%
2005	68	415	2.83%	17.26%	59	300	3.12%	15.88%	43	271	4.30%	27.07%
2006	90	505	3.74%	21.00%	53	353	2.81%	18.69%	43	314	4.30%	31.37%
2007	78	583	3.24%	24.24%	67	420	3.55%	22.23%	45	359	4.50%	35.86%
2008	69	652	2.87%	27.11%	46	466	2.44%	24.67%	48	407	4.80%	40.66%
2009	143	795	5.95%	33.06%	49	515	2.59%	27.26%	51	458	5.09%	45.75%
2010	110	905	4.57%	37.63%	51	566	2.70%	29.96%	63	521	6.29%	52.05%
2011	104	1009	4.32%	41.95%	54	620	2.86%	32.82%	64	585	6.39%	58.44%
2012	118	1127	4.91%	46.86%	51	671	2.70%	35.52%	71	656	7.09%	65.53%
2013	190	1317	7.90%	54.76%	56	727	2.96%	38.49%	67	723	6.69%	72.23%
2014	157	1474	6.53%	61.29%	98	825	5.19%	43.67%	57	780	5.69%	77.92%
2015	206	1680	8.57%	69.85%	177	1002	9.37%	53.04%	55	835	5.49%	83.42%
2016	290	1970	12.06%	81.91%	241	1243	12.76%	65.80%	57	892	5.69%	89.11%
2017	247	2217	10.27%	92.18%	303	1546	16.04%	81.84%	47	939	4.70%	93.81%
2018	188	2405	7.82%	100.00%	343	1889	18.16%	100.00%	62	1001	6.19%	100.00%
Stdev	70.9	–	–	–	93.6	–	–	–	11.36	–	–	–
Min	51	–	–	–	35	–	–	–	32	–	–	–
Max	290	–	–	–	343	–	–	–	71	–	–	–
Average	120	–	–	–	94.5	–	–	–	50.05	–	–	–
Sum	2405	–	–	–	1889	–	–	–	1001	–	–	–

Notes: NP= Number of publications | CNP=Cumulative number of publications | % sum = Number of publications in the year/total number of publications | %cum = Cumulative number of publications/total number of publications | Stdev = standard deviation.

safety research, where the size of the nodes and labels are proportionate with the number of occurrences of a country/region. Three large groups are identified in the collaboration network, based on the collaboration strength of these countries/regions, see Fig. 6(a). The average publication year of each country/region is shown in Fig. 6(b). Table 3 lists the top 10 most productive countries/regions in international process safety research, corresponding to the network in Fig. 6.

The results of Fig. 6(a) indicate that USA is the most productive country in process safety research, with 1230 papers, amounting to 23.23% of the total. The USA is followed by China (857,16.19%) and the United Kingdom (583, 11.01%). In this figure, the countries/regions in the same cluster are more closely connected in the process safety research. For instance, the Netherlands, the United Kingdom, Italy, Spain, and Germany form a cluster of European countries. As shown in Fig. 6(b), the average publication year of the countries/regions show that People R China, Iran, Malaysia, and Brazil currently are active



(a) Cluster of collaboration network of countries/regions in PS research

(b) Average publication year of each country/region

Fig. 6. Collaboration network of high productive countries/regions in process safety research, based on publications in JLPPI, PSEP, and PSP in the period 1999–2018.

countries/regions in process safety research. In terms of the average number of citations, Table 3 indicates that contributions by Canada have the highest average impact, followed by India and Italy. The average citation rate of countries with higher productivity, such as USA and Peoples R China, is comparatively lower.

The process safety research was driven by the development of the chemical industry, and by high-profile industrial accidents in developed countries, such as the Flixborough disaster (UK, 1974) and the Seveso disaster (Italy, 1976). Developed countries such as the United Kingdom, USA, Germany, Italy, and Japan have had a mature chemical industry already for decades. Research on process safety in these countries has a longer history, as seen in the earlier average publication year of these. On the other hand, People R China, Iran, Malaysia, Brazil and India are developing countries where the chemical industry and the process industries have been growing fast in recent years. It appears plausible that safety considerations have increasingly become more important in these developing chemical and process industries, and that process safety research has attracted more attention, and obtained more financial support, in these countries/regions.

International collaboration is a good way to transfer knowledge and expertise between different countries/regions. The developing countries/regions can learn process safety methods and techniques, and gain knowledge about technological, social, and organizational advances from developed countries/regions to improve the safety status of their

Table 3
Top 10 high productive countries/regions in process safety research.

No.	Countries/regions	Continent	NP	%	TC	Avg. pub. year	Avg. citations
1	USA	N. America	1230	23.23%	9533	2010.46	7.75
2	Peoples R China	Asia	857	16.19%	8463	2014.63	9.88
3	United kingdom	Europe	583	11.01%	7694	2008.25	13.20
4	Italy	Europe	286	5.40%	4187	2011.31	14.64
5	Canada	N. America	275	5.19%	4858	2011.57	17.67
6	India	Asia	266	5.02%	4468	2013.04	16.80
7	France	Europe	241	4.55%	2862	2011.09	11.88
8	Iran	Asia	227	4.29%	2900	2015.07	12.78
9	Germany	Europe	174	3.29%	1808	2010.08	10.39
10	Japan	Asia	168	3.17%	1949	2009.92	11.60

process industries. Apart from collaborations between developed countries such as the United Kingdom, USA, Canada, Italy, and Germany, there are also emerging international collaboration networks between developed countries/regions and developing countries/regions, e.g. between USA, Canada, the Netherlands, United Kingdom, and People R China, and between USA and Canada, and Brazil.

Fig. 7 shows the collaboration network between the key institutions' contribution to process safety research. Fig. 7(a) show the clusters of the institutions in the research domain, whereas Fig. 7(b) provides insights in the average publication year of each institution. Table 4 lists the top 10 most productive institutions in process safety research.

According to the results of Table 4, Texas A&M Univ has published 225 papers, amounting to 4.25% of the global total, thereby ranking first place in the international process safety research. It is followed by Mem Univ Newfoundland (120, 2.27%) and China Univ Min & Technol (75, 1.42%). Texas A&M Univ is the leading institution in process safety research and has a research center dedicated to process safety research: the Mary Kay O'Connor Process Safety Center. It hosted or hosts some of the outstanding researchers in process safety, including Sam Mannan, Hans Pasman, and William Rogers. Mem Univ Newfoundland from Canada also famous in process safety, with Faisal Khan being the group's key contributor. In terms of the average number of citations, the results indicate that contributions by Dalhousie Univ and Mem Univ Newfoundland by far have the highest average impact, with leading academics Paul Amyotte and Faisal Khan leading the process safety research efforts in these institutions.

As evident from Table 4 and Fig. 7(b), Chinese institutions have increasingly paid more attention to process safety research, with 4 universities from mainland China ranking among the top 10 most productive institutions. It is furthermore seen that there are also some companies which provide significant contributions to process safety research, e.g. Gexcon, Baker Engn & Risk Consultants Inc, Dow Chem Co USA, and Air Prod & Chem Inc. The average publication year shows that the institutions from mainland China (e.g. China Univ Min & Technol, China Univ Petr, Nanjing Tech Univ, Henan Polytech Univ, Beijing Inst Technol, Chinese Acad Sci, and Dalian Univ Technol) and from Europe (KU Leuven, Univ Antwerp, Delft Univ Technol) are recently active in the research field.

The network also shows that institutions from the same country/region commonly have closer collaboration relations than institutions in different regions. For instance, Chinese institutions are mainly located at the top end of the collaboration network figures; whereas institutions from the USA are located in the center of the network, and institutions from Canada and Europe are found on the right bottom of the network. In the network, Mem Univ Newfoundland and Dalhousie Univ; and Delft Univ Technol, KU Leuven and Univ Antwerp have a significantly higher collaboration strength compared with other institutions. The latter is the case due to the leading academic Genserik Reniers being simultaneously affiliated with the three universities.

3.3. Terms co-occurrence analysis

Noun phrase in the titles and abstracts of papers from three process safety related journals are extracted based on the automatic term identification method by van Eck et al. (2010b). A terms co-occurrence network is created based on terms which occur at least ten times in the complete dataset. Finally, 1309 terms are extracted using this threshold of the terms' frequency.

The terms co-occurrence network of the combined dataset of the three target process safety journals (JLPPI, PSEP, and PSP) is shown in Fig. 8. The colors of each node indicate the different clusters to which the terms belong, whereas the node and label sizes are proportional to the terms' occurrence frequencies. A term is assigned to only one cluster (the one to which it links most strongly), but can also have strong links to other clusters, in which case it will usually be located closely to the other cluster. Take for instance the term 'experiment', which belongs to the blue cluster (Cluster #3) and links strongly to very many terms within that cluster (e.g. 'dust', 'ignition', 'mixture', 'air', etc.). This terms also links strongly to the green cluster (Cluster #2), and hence is located closely to it, linking with green-colored terms such as 'temperature', 'reaction', 'flow rate', etc. In Fig. 8, no axes are shown as the visualization applies a normalized distance between the terms, where terms located closer to one another are generally more closely related, see van Eck et al. (2010b).

Three large term clusters are identified, and the authors have given each cluster a name to provide a narrative interpretation of what are the high-level focus areas within the process safety domain. This is done based on the terms inside the clusters, and involves some subjectivity based on the authors' knowledge and experience of the research domain. In this interpretation, mainly the terms with a higher occurrence frequency are given more weight, while in the choice of a cluster name the authors also aimed to formulate a label which also covers the less frequently occurring terms. It is also worth noting that because the terms are extracted from throughout the articles' text, the clusters should be understood broadly as narrative patterns rather than research topics specifically. Hence, it is possible that some terms in the clusters are not associated with research results per se, but rather with a discussion on the need for those.

Cluster #1 is given the name "Process safety risk management" and includes 525 terms. Cluster #2 is labeled as "Chemical process safety" and includes 416 terms. Cluster #3 concerns "Fire and explosion process safety" and includes 368 terms. As seen in the top-left image in Fig. 8, Cluster #2 and cluster #3 are located close to each, which reflects that the work in these is more closely linked than the work in cluster #1. Generally, A brief interpretation of three clusters is presented below.

■ Cluster #1 Process safety risk management

This cluster, shown in red in Fig. 8, is concerned with the occurrence of incidents and accidents on the level of an integrated system, and on interdisciplinary management-level approaches to prevent losses. It focuses on the management of risks and safety, for which activities such as

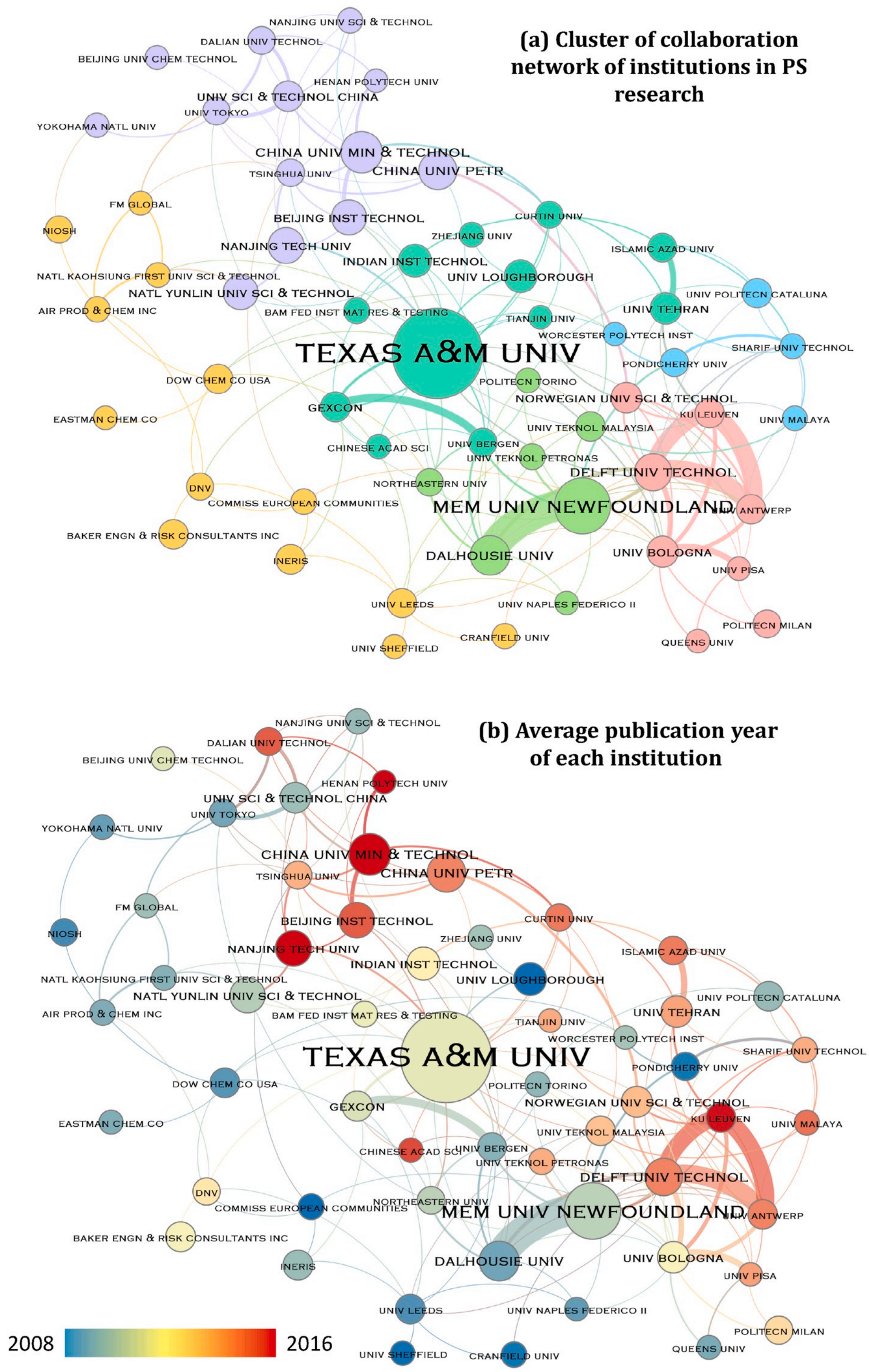


Fig. 7. Collaboration network of high productive institutions in Process Safety research, based on publications in JLPPI, PSEP, and PSP in the period 1999–2018.

accident investigation, maintenance, safety management, risk management, and inspections, are in focus. Specific focus topics include process hazard analysis, protection analysis, and consequence analysis, where event occurrences (e.g. causes, failures, operator and maintenance related issues) and the associated consequences (injuries, accidents) are analyzed and considered in a decision-making context. Case studies are an important focal point, and methods such as HAZOP, fault trees, Bayesian networks, and analytic hierarch process are used for this purpose. Quantitative analyses of risk constitute an important narrative in this cluster. This cluster is strongly interdisciplinary, and includes knowledge from natural sciences, engineering, and social and organizational sciences.

■ Cluster #2 Chemical process safety

This cluster, shown in green in Fig. 8, is concerned with the safety of chemical processes, and has a more disciplinary focus compared to Cluster #1, with a more applied science and chemical engineering character. Experiments and studies on process parameter settings and optimization appear to be the focus of this cluster, aiming to build and discuss knowledge related to the safety of chemical processes. The cluster includes terms from chemistry such as solution, adsorption,

Table 4
Top 10 high productive institutions in Process Safety research.

NO.	Institutions	Countries/regions	NP	%	TC	Avg. pub. year	Avg. citations
1	Texas A&M Univ	USA	225	4.25%	2673	2012.48	11.88
2	Mem Univ Newfoundland	Canada	120	2.27%	3132	2011.82	26.10
3	China Univ Min & Technol	China	75	1.42%	739	2016.27	9.85
4	Dalhousie Univ	Canada	69	1.30%	1945	2010.03	28.19
5	China Univ Petr	China	65	1.23%	752	2014.83	11.57
6	Delft Univ Technol	Netherlands	62	1.17%	478	2014.84	7.71
7	Nanjing Tech Univ	China	58	1.10%	250	2016.53	4.31
8	Beijing Inst Technol	China	56	1.06%	527	2015.23	9.41
9	Natl Yunlin Univ Sci & Technol	Taiwan	55	1.04%	501	2011.69	9.11
10	Indian Inst Technol	India	49	0.93%	597	2013.14	12.18

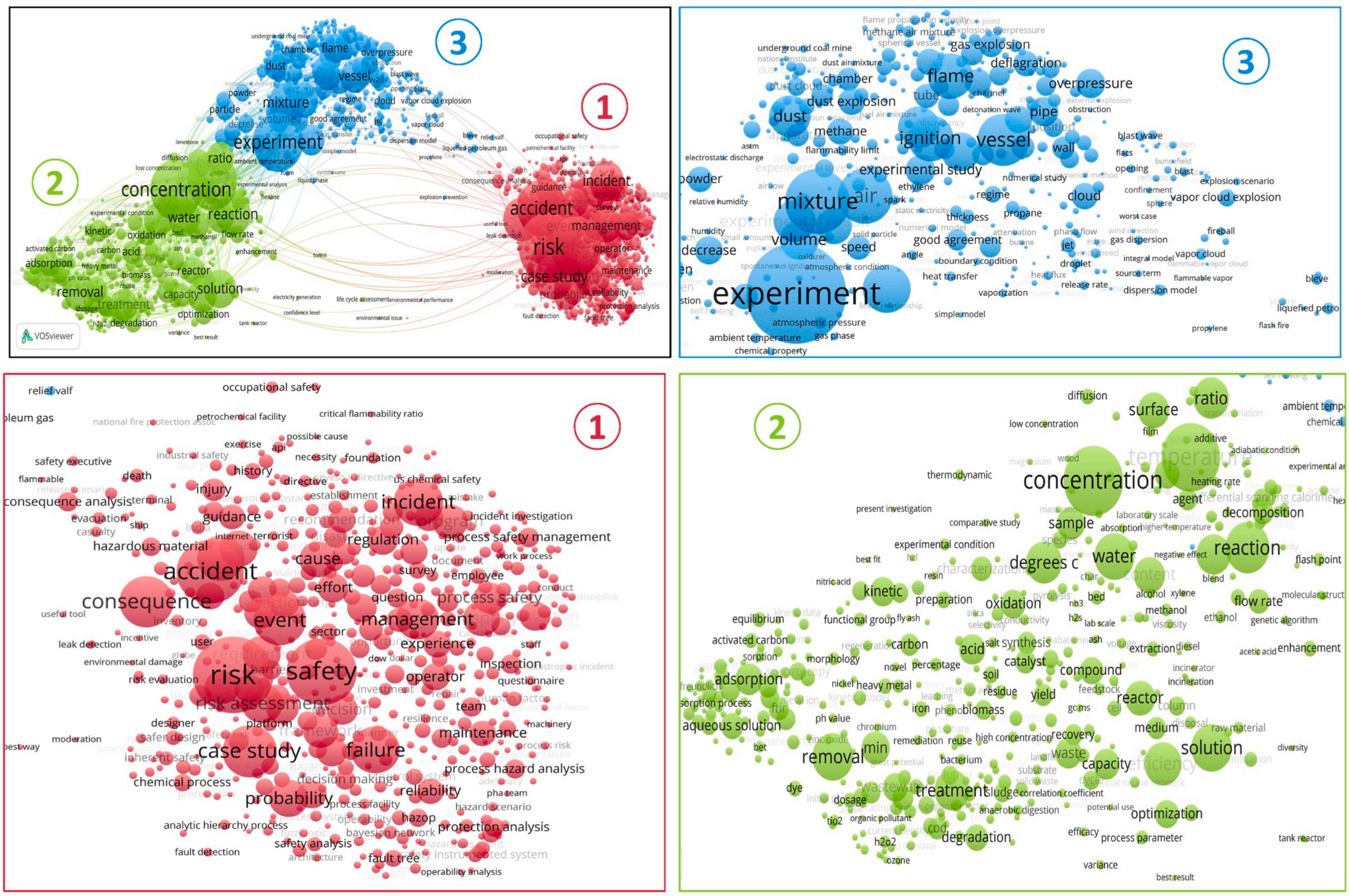


Fig. 8. Terms co-occurrence clusters of the three target Process Safety journals, based on publications in JLPPI, PSEP, and PSP in the period 1999–2018.

reaction, degradation, and process-related terms such as temperature, concentration, equilibrium, flow rate, pH-value, and catalyst. Various chemical products and elements appear in the term cluster, for instance H2O2, TiO2, H2S, NH3, iron, and nickel. This cluster has linkages to the "Process safety risk management" cluster but is more closely linked to the "Fire and explosion process safety" cluster, especially through terms related to experimentation and experimental conditions.

■ Cluster #3 Fire and explosion process safety

This cluster, shown in blue in Fig. 8, focuses on the fire and explosion related safety of process safety. As Cluster #2, it has a more disciplinary focus than Cluster #1, and appears to have a more applied science and engineering focus. Experiments and studies about the conditions under which various types of fires and explosions occur are important narratives in this cluster, to build and discuss knowledge about safe conditions of process operation and about the consequences in case fires and explosions occur. The cluster includes terms focusing on the type of phenomenon under study, for instance flame, deflagration, dust explosion, vapor cloud explosion, detonation wave, blast wave, and BLEVE (boiling liquid expanding vapor explosion). Different substances or products are the focus of investigations, including dust, methane mixtures, ethylene, and propylene. Experiments are an important focus point in this cluster, but also modeling work and numerical studies are included. Issues such as ignition, cloud and air mixtures, boundary conditions, flammability limits, overpressure, and physical layout of chambers, pipes, and walls, are the key topics, which are important both in experimental and modeling contexts. This cluster has linkages to the "Process safety risk management" cluster but is more closely linked to the "Chemical process safety" cluster, especially through terms related to experimentation and experimental conditions.

Terms overlay maps of the process safety research domain are shown in Fig. 9, giving insights in the temporal evolution of the research domain, the topics with high research impact, and the focus topics of each of the three target process safety journals. Fig. 9 has the same structure as Fig. 8 and provides further insights in the developments and impacts of different topics within the three clusters identified above.

The temporal evolution of scientific attention to topics within process safety is shown in Fig. 9(b). An overlay of the term co-occurrence map is applied, showing the average year in which the term occurs. A blue color represents older terms, with 2010 the average year of use. A red color denotes 2015 as the average year of use, i.e. more recent. This overlay clearly shows there is ongoing activity in all three clusters identified in Fig. 8. Overall, cluster #2 "chemical process safety" shows most recent activity, with terms such as adsorption process, aqueous solution, wastewater treatment, degradation, and optimization recent focus issues. Activity in cluster #3 "Fire and explosion process safety" shows a mixture of recent and older activity, with specific recent focus topics including explosion overpressure, flame propagation velocity, and methane air mixture. Cluster #1 "Process safety risk management" contains comparatively more older topics, with an initial focus on incidents, incident investigation, and safety management. Contemporary research frontiers in this cluster focus on Bayesian Networks and fault detection. Naturally, focusing only on the average year in which a term is used may give a somewhat distorted view, especially if there are terms which have a large standard deviation (i.e. topics which were in focus early on and continue to be in focus to the present). Nevertheless, in scientometric analyses, it is common to use the average value as an indicator to compare the temporal evolution of activity on different topic area, see e.g. Li et al. (2020).

Fig. 9(c) shows a terms co-occurrence map with an overlay of the average citations of the papers in which the terms occurred, providing insights in which research issues have attracted significant attention and are influential in the further development of the field. It shows that terms in cluster #2 "Chemical process safety" overall have higher citation rates, i.e. that it is not only a more recent area of research activity, but also relatively more impactful. Hence, it can be concluded that cluster #2 is the current hot research domain within process safety. Cluster #3 "Fire and explosion process safety" contains few very impactful research topics, but terms related to dust explosions are comparatively more impactful than other fire or explosion related topics. Within cluster #1 "Process safety risk management", probabilistic approaches to accident risk assessment and consequence analysis appear more impactful than safety management and incident investigation, with especially methodologically focused topics such as fault trees and Bayesian Networks being highly influential.

In the current research, the data from three process safety journals is collected and the combined terms co-occurrence map is shown in Fig. 9 (a). It is also instrumental to obtain insights in focus topic areas of each journal compared to the other ones. This is analyzed in Fig. 9(d–f), where an overlay is applied indicating the relative occurrence rate of a term in each journal compared to the overall occurrence rate in the

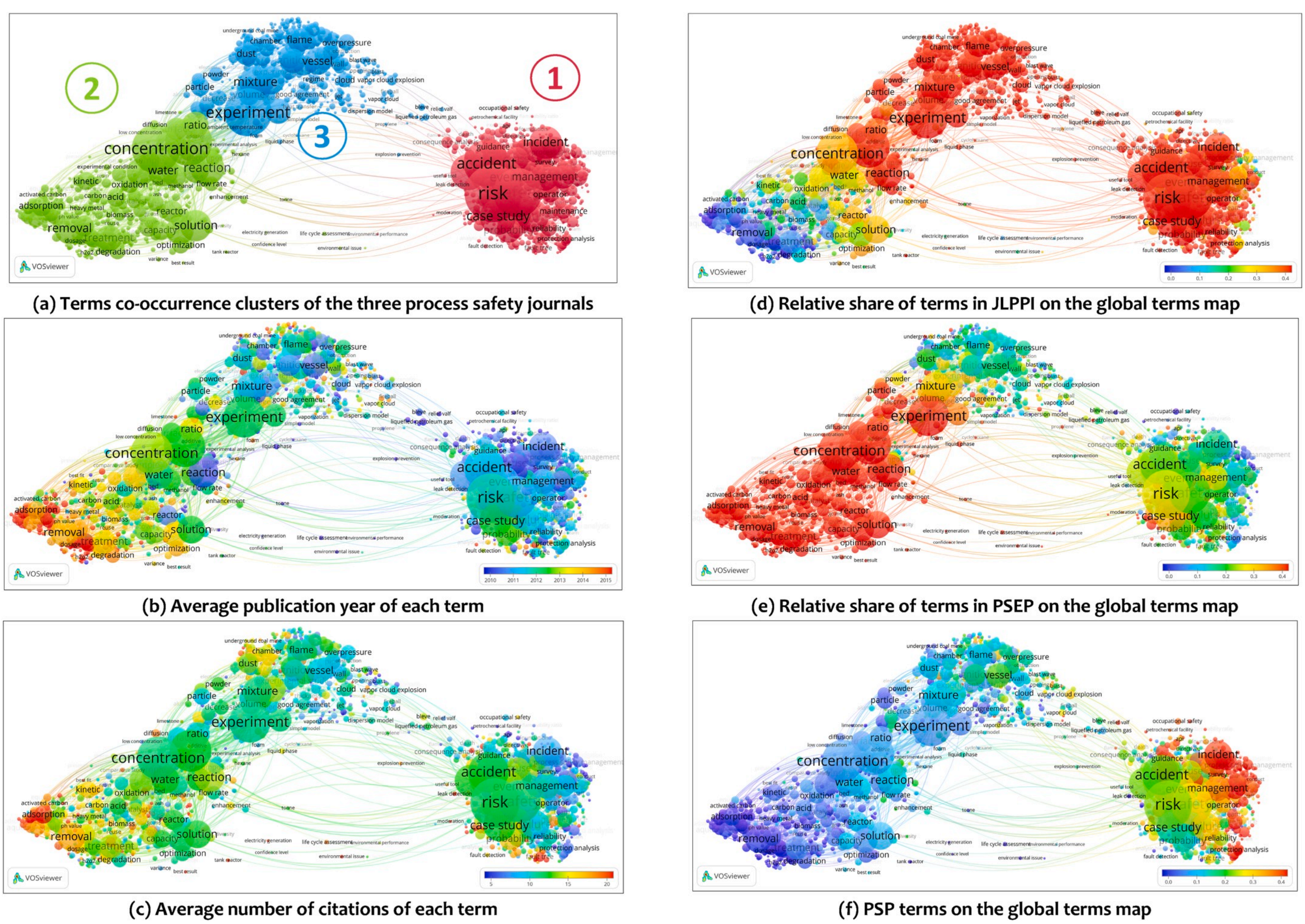


Fig. 9. Terms co-occurrence clusters of the three target Process Safety journals: temporal evolution, impact, and journal focus topics, based on publications in JLPPI, PSEP, and PSP in the period 1999–2018.

complete dataset. In these figures, when a term's node color is close to red, this means that the term has a high occurrence percentage in the target journal. For example, the total occurrence rate of the term 'experiment' (located in cluster #2) is 693 across the three journals. Of these, 53% is contributed by JLPPI, 40% by PSEP, and 7% by PSP. Hence, in the figures red areas signify topics where a journal has an important contribution to the process safety research areas, whereas for blue areas, the journal has little or no contribution.

It is seen from Fig. 9(e) that JLPPI has a significant contribution to all topic clusters, especially to cluster #1 "Process safety risk management" and cluster #2 "Fire and explosion process safety". Considering also the temporal evolution and impact overlay maps of Fig. 9(b) and (c), JLPPI however has almost no contribution to the currently important research topics related to chemical process safety. The analysis shows that PSEP has more focus on cluster #3 "Chemical process safety" compared to the JLPPI and PSP, and that this focus on impactful topics of contemporary importance is an important contributing factor to the rapidly increasing journal impact factor as found in Fig. 1. PSEP also has important contributions to the other clusters. Finally, PSP has a less diversified area of research activity, with most of its publications located in cluster #1 "Process safety risk management", and to a lesser extent in cluster #2 "Fire and explosion process safety". Moreover, the highest share of contribution within the process safety research domain is on topics with less contemporary attention or impact. These topics are located on the right end side of cluster #1, and concern incident analysis and safety management. While PSP also contains a relatively important share of the research in cluster #2 "Fire and explosion process safety", which is more impactful and of recent interest, this does not suffice to lead to a significantly growing journal impact factors, as found in Fig. 1. This analysis clearly shows that different leading journals within process safety, which in principle address similar topics within their journal scope, in fact do have markedly different research focus areas and associated impact. Such information can be useful especially for journal editors and editorial boards to position their journal within the research domain. It can also be useful for prospective authors to select a suitable journal for their work, by seeing which journal best aligns with the focus topic of their work, and how active journals are on the topic.

3.4. Intellectual base analysis

3.4.1. Highly cited sources

Highly cited sources are journals, books or other media that are frequently cited in process safety research, where journals are the main source being cited in scientific papers. Highly cited sources reflect the main knowledge carriers that support the process safety research and can be regarded as its intellectual base. In this Section, highly cited sources are obtained from the reference lists of the 5295 papers. A total of 36,745 unique sources are extracted, of which sources with more than 500 citations are selected as the target for constructing the journals co-citation network.

The sources co-citation network of process safety is shown in Fig. 10, where the nodes and label sizes are used to show the number of citations of a source. In the network, the three target process safety journals are marked with a circle, and arrows indicate the citations to the target journals from other journals.

Four clusters of sources are identified based on the sources' co-citation strength: hazard & environment, chemical, combustion and fire, and process and system safety. The highly cited sources in each cluster are listed in Table 5. According to Fig. 10 and Table 5, JLPPI with 8192 citations, is the most cited journal in process safety research based on number of citations in the period 1999–2018, followed by J Hazard Mater, PSEP, PSP and Reliab Eng Syst Safe. Thus, three of the top 5 highly cited journals within process safety research are the journals in

Table 5
High cited sources of Process Safety related journals in each cluster.

Cluster	Cluster name	List of sources (number of citations)
1	Hazard and Environment	J Hazard Mater (5547), Bioresource Technol (1500), Chem Eng J (1465), Water Res (1456), Environ Sci Technol (981), Chemosphere (786), Desalination (758), Water Sci Technol (524), Sep Purif Technol (521).
2	Combustion and fire	Combust Flame (1692), Fuel (1029), Int J Hydrogen Energ (751), Combust Sci Technol (542), P Combust Inst (534), Fire Safety J (511).
3	Process and system safety	JLPPI (8192), PSEP (2935), PSP (2391), Reliab Eng Syst Safe (1906), Safety Sci (1507).
4	Chemical	Ind Eng Chem Res (1278), Chem Eng Sci (829), Comput Chem Eng (751), Aiche J (663).

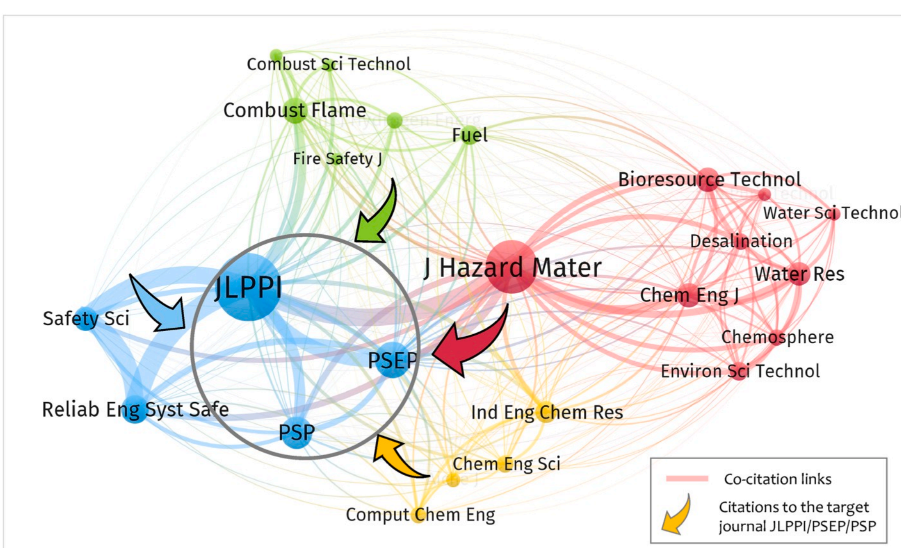


Fig. 10. Highly cited sources in the three journals JLPPI, PSEP, and PSP, 24 journals with more than 500 citations extracted from the references lists of these journals.

focus in this work, indicating that these are well selected as a basis for providing insights in the process safety research domain. The results also show that J Hazard Mater and Reliab Eng Syst Safe have transferred more knowledge to the process safety research than other journals.

The blue cluster in Fig. 10, labeled "process and system safety" can be regarded as the core group in process safety research, and it contains the three selected process safety journals JLPPI, PSEP, and PSP. The strengths of the co-citation links of these journals show that these core process safety journals strongly interact with *Safety Science* and *Reliability Engineering & System Safety*. The cited sources can be regarded as the intellectual base in process safety research.

The top 10 highly cited sources of each target process safety journals are shown in Fig. 11. This is used to show the intellectual base of sample journals in process safety research. It is evident that the most cited sources of each journal are the journal itself, except for PSEP. J Hazard Mater is the most cited journals in PSEP papers, which means that J Hazard Mater is the key knowledge source to support research published in PSEP. JLPPI, PSEP and PSP appeared in the top 10 cited sources in JLPPI and PSP, while PSP was not listed among the top 10 cited sources in PSEP. This means that the papers published in PSP cited more papers from PSEP, but that this relationship is not reciprocal. In JLPPI, Fuel and Int J Hydrogen Energ are listed in the top 10 cited journals, but these are not listed the top 10 in PSEP and PSP. PSEP includes six journals which are listed only in its highly cited sources list, i.e. those six journals are not significant knowledge contributors to JLPPI and PSP. These differences in journals as intellectual bases for the three target process safety journals confirms the findings of Section 3.3 and Fig. 8 that the three journals have different focus domains in the topic clusters within the process safety research domain.

3.4.2. *Highly cited references*

Highly cited works, here defined as publications with minimum 20 citations received from articles within the dataset of articles published in the three target process safety journals, can be considered as the intellectual basis of process safety. Using these criteria, a total of 127 highly cited references are obtained and identified from the 101,599 references listed by all articles in the complete dataset. A co-citation network of these highly cited references is constructed and shown in Fig. 12. Here, each node represents a reference, where the size is proportional to the number of citations received from the publications in JLPPI, PSEP, and PSP in the period 1999–2018. The main label here shows the first author and publication year of a publication, where the sublabel signifies the name of the journal or book. The links between the nodes represent the co-citation relations between these highly cited references. The width of the links gives an indication of the co-citation strength between these papers. The colors show different groups of these references, with clusters based on the co-citation strength of these references, using the algorithm by Waltman et al. (2010). The top-5 most highly cited articles of each cluster included in this co-citation network are listed in Table 6. Fig. 13 shows an overlap mapping of the highly cited reference clusters, indicating the annual number of citations to these publications from the dataset obtained from the three target process safety journals.

This analysis indicates that there are five clusters in the highly cited references of the three target process safety journals. Cluster #A, marked in red in Fig. 12, contains significant works addressing dust explosions, and is labeled as "Dust explosions". The most cited work in this cluster is the book by Eckhoff (2003) on the identification, assessment, and control of dust explosion hazard, which focuses on the activities, testing methods, and designs for safe operation, as well as insights in the different physical phases of dust explosions. Significant articles include the study of pressure generation mechanisms in vented explosions by

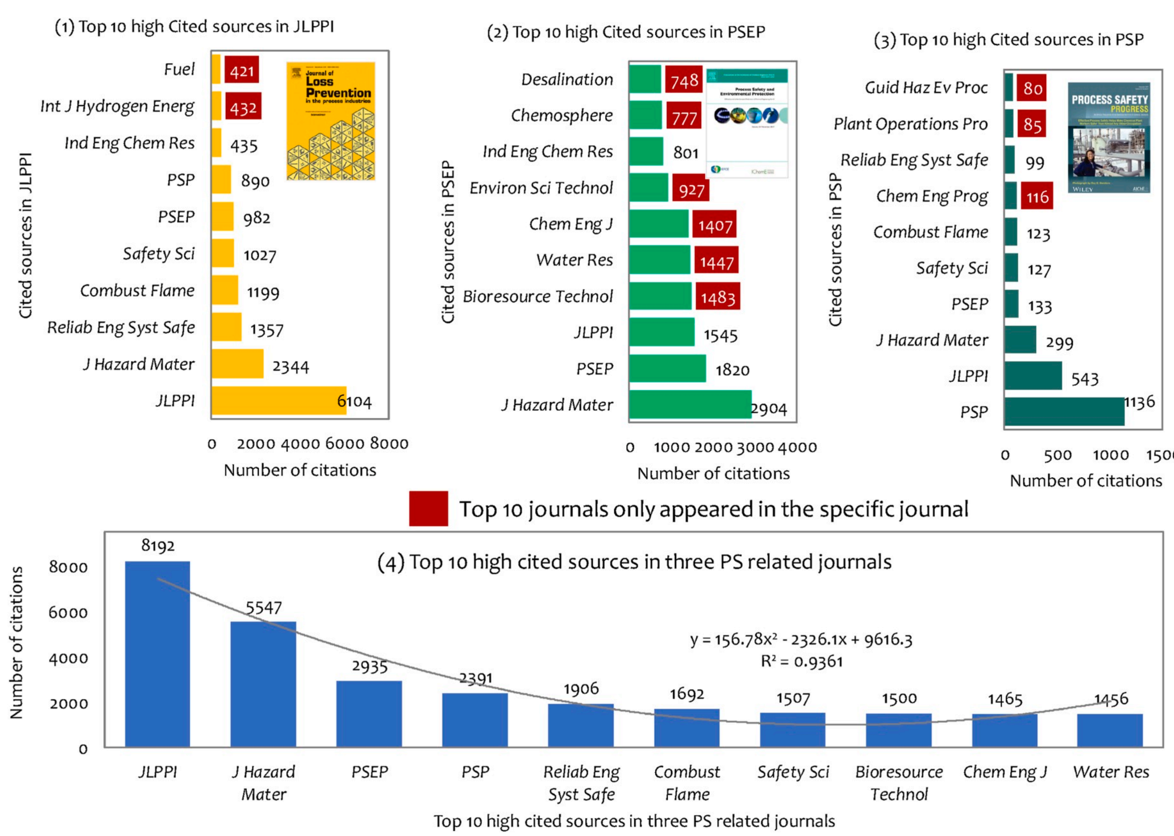


Fig. 11. Top 10 high cited sources in each of the three process safety journals, CSJLPPI = Cited Sources in JLPPI | CSPSEP = Cited Sources in PSEP | CSPSP = Cited Sources in PSP | CS3J = Cited Sources in 3 journals.

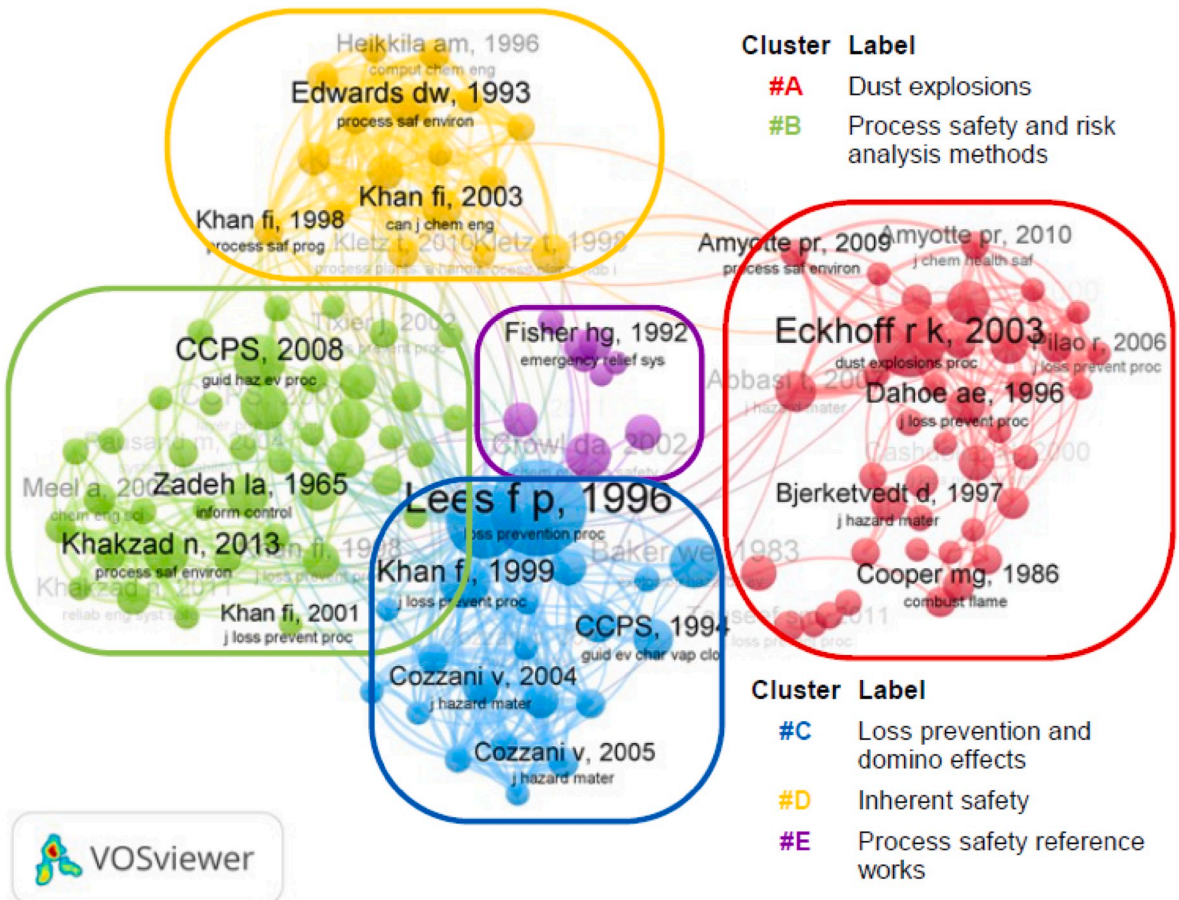


Fig. 12. Co-citation network of highly cited reference clusters based on co-citation strength, labels indicate first author and publication year, sub-labels indicate the article's source journal, based on reference list of publications in JLPPI, PSEP, and PSP in the period 1999–2018.

Cooper et al. (1986), the work on coal dust explosibility by (Cashdollar, 1996), the work on flame thickness in dust explosions by Dahoe et al. (1996), and the study of cork dust explosibility in methane/air mixtures by Pilao et al. (2006). Significant overview or review articles include the gas explosion handbook by Bjerketvedt et al. (1997), the work on dust explosibility characteristics by (Cashdollar, 2000), and the overview of cases, causes, consequences, and control of dust explosions by Abbasi and Abbasi (2007). Other impactful work in this cluster concerns the CFD simulation of gas dispersion near obstacles by Tauseef et al. (2011), and the work by Amyotte et al. (2009) linking dust explosions with inherent safety principles. This cluster is closely related to cluster #3 "Fire and explosion process safety" in Section 3.3 and Fig. 7.

Cluster #B in Fig. 12, marked in green, is labeled "Process safety and risk analysis methods", as it primarily concerns techniques and modeling approaches for analyzing the risks and safety in chemical and process industries. The most influential works in this cluster are the books by Center for Chemical Process Safety (CCPS) on layer of protection analysis (CCPS, 2001) and the guidelines for hazard evaluation procedures (CCPS, 2008). Another influential book is the book by Reason (1997) on the management of risks of organizational accidents, where the 'Swiss Cheese' model of organizational accidents is outlined, and the book by (Rausand and Høyland, 2003) on system reliability theory. Early reviews on techniques and methodologies for risk analysis in chemical process industries and industrial plants by (Khan and Abbasi, 1998) and (Tixier et al., 2002) are influential. Impactful original research is the work by Zadeh (1965) on fuzzy sets, the application of Bayesian theory to the estimation of failure probabilities by (Meel and Seider, 2006), the comparison of fault trees and Bayesian networks for process safety analysis by Khakzad et al. (2011), and the method for mapping bow-tie analysis in a Bayesian network by (Khakzad et al., 2013). This cluster is closely related to cluster #1 "Process safety risk management" in Section 3.3 and Fig. 8.

Cluster #C in Fig. 12, marked in blue, is labeled "Loss prevention and domino effects". It contains a mix of comprehensive overview publications focusing on major accident hazards, and more specific original contributions on modeling approaches and strategies for analyzing and managing the risks of domino accidents. Important compendia works in this cluster include the book on explosion hazards by (Baker et al., 1983), the guidelines on vapor cloud explosions, flash fires and BLEVEs by CCPS (1994), the standard work on loss prevention in the process industries by Lees (1996), and the guidelines on chemical process quantitative risk analysis by CCPS (2000). The research by (Khan and Abbasi, 1999)on the common causes and consequences of a number of major accidents in the process industries which occurred during the 20th century is also highly influential in this cluster. The most significant original research contributions in this cluster concerns the work by Valerio Cozzani and his collaborators related to domino effects. In (Cozzani and Salzano, 2004), probit models are derived for domino effects caused by overpressure (Cozzani et al., 2005), present a procedure and software package for quantitative risk assessment of domino effects, and (Cozzani et al., 2007) links domino effects with inherently safe design. This cluster is closely related to cluster #1 "Process safety risk management" in Section 3.3 and Fig. 8, but also refers to knowledge of cluster #3 "Fire and explosion process safety".

Cluster #D in Fig. 12, marked in yellow, is labeled "Inherent safety". It contains a handbook for inherently safe designs by Kletz (1998),

Table 6
Top 5 highly cited references in each cluster of three Process Safety journals.

Author-Year	Title	Source journal	Cluster	Citations	Year	Ave. Citations
Eckhoff (2003)	Dust explosions in the process industries	Dust Explosions Proc	A	98	2003	5.76
Cashdollar (2000)	Overview of dust explosibility characteristics	J Loss Prevent Proc	A	48	2000	2.40
Abbasi and Abbasi (2007)	Dust explosions-cases, causes, consequences, and control	J Hazard Mater	A	44	2007	3.38
Cashdollar (1996)	Coal dust explosibility	J Loss Prevent Proc	A	38	1996	1.58
Dahoe et al. (1996)	Dust explosions in spherical vessels: the role of flame thickness in the validity of the 'cube-root law'	J Loss Prevent Proc	A	38	1996	1.58
CCPS (2008)	Guidelines for hazard evaluation procedures	Guid Haz Ev Proc	B	60	2008	5.00
CCPS (2001)	Layer of protection analysis: simplified process risk assessment	Layer Prot An Simpl	B	53	2001	2.79
Khakzad et al. (2013)	Dynamic safety analysis of process systems by mapping bowtie into Bayesian network	Process Saf Environ	B	48	2013	6.86
Zadeh (1965)	Fuzzy sets	Inform Control	B	45	1965	0.82
Reason (1997)	Managing the risks of organizational accidents	Managing Risks Org A	B	41	1997	1.78
Lees (1996)	Loss prevention in the process industry	Loss Prevention Proc	C	147	1996	6.13
CCPS (2000)	Guidelines for chemical process quantitative risk analysis	Guid Chem Proc Quant	C	103	2000	5.15
(W.E. Baker et al., 1983)	Explosion hazards and evaluation	Explosion Hazards Ev	C	58	1983	1.57
Khan and Abbasi (1999)	Major accidents in process industries and an analysis of causes and consequences	J Loss Prevent Proc	C	58	1999	2.76
CCPS (1994)	Guidelines for evaluating the characteristics of vapor cloud explosions, flash fires and BLEVEs	Guid Ev Char Vap Clo	C	41	1994	1.58
Edwards and Lawrence (1993)	Assessing the inherent safety of chemical process routes: is there a relation between plant costs and inherent safety?	Process Saf Environ	D	45	1993	1.67
Khan and Amyotte (2003)	How to make inherent safety practice a reality	Can J Chem Eng	D	42	2003	2.47
Kletz (1998)	Process plants: a handbook of inherently safer designs	Process Plants Hdb I	D	41	1998	1.86
Khan and Amyotte (2004)	Integrated Inherent Safety Index (i2si): A Tool for Inherent Safety Evaluation.	Process Saf Prog	D	37	2004	2.31
Khan and Amyotte (2005)	I2si: A Comprehensive Quantitative Tool for Inherent Safety and Cost Evaluation	J Loss Prevent Proc	D	32	2005	2.13
Crowl and Louvar (2002)	Chemical process safety: fundamentals with applications	Chem Process Safety	E	50	2002	2.78
Mannan (2005b)	Lees' loss prevention in process industry	Lees Loss Prevention	E	35	2005	2.33
Crowl and Louvar (2011)	Chemical process safety: fundamentals with applications	Chem Process Safety	E	34	2011	3.78
Fisher et al. (1992)	Emergency relief system design using diers technology	Emergency Relief Sys	E	33	1992	1.18
Townsend and Tou (1980)	Thermal hazard evaluation by an accelerating rate calorimeter	Thermochim Acta	E	33	1980	0.83

which has a second edition authored by (Kletz and Amyotte, 2010). Early influential works in this cluster include the work by Edwards and Lawrence (1993) on the relation between plant costs and inherent safety, and the method by (Heikkilä et al., 1996) which combines process rules with safety rules for process pre-design (Khan and Amyotte, 2003). provide an overview of inherent safety principles and campaigns to raise awareness and interest in the approach in North-America, describe available tools, and discuss pathways to its more widespread use (Khan and Amyotte, 2004). present new research on the Integrated Inherent Safety Index (I2SI) tool, which is extended further to include economic considerations in (Khan and Amyotte, 2005). This cluster is most closely related to cluster #1 "Process safety risk management" in Section 3.3 and Fig. 8.

Finally, cluster #E, colored in purple in Fig. 12 and located in the center, is labeled "Process safety reference works" as it primarily contains compendia works, such as the book by (Fisher et al., 1993) on emergency relief system design technology, the standard work by Lees on loss prevention in the process industries as updated by Mannan (2005a), and the books on chemical process safety by Crowl and Louvar (2002, 2011). The article by (Townsend and Tou, 1980) on thermal hazard evaluation using accelerating rate calorimeter is not a compendium, but the technique is very influential in chemical process safety, and can hence also be considered as a kind of standard work.

4. Conclusions

Research on safety in the chemical and process industries has a rich and varied history, and a very impressive body of knowledge has been created to increase the understanding of various hazardous phenomena, techniques and methods to analyze their occurrence probability and consequences, and technologies and processes to reduce the risks to human life and the environment.

In this article, a retrospective overview of the process safety research field has been presented, through the lens of three process safety related journals: *Journal of Loss Prevention in the Process Industries*, *Process Safety and Environmental Protection*, and *Process Safety Progress*. A scientometric analysis of their combined publications in the period 1999–2018 has been performed, providing insights in the structure, main themes, and influential works in the process safety domain.

A first finding is that all three journals have gradually published an increasing number of articles, with especially PSEP, and to a lesser extent JLPPI, having seen a marked increase from 2008 onwards. Concurrently, the journal impact factors of these two journals has rapidly increased since then. The geographic distribution of countries/

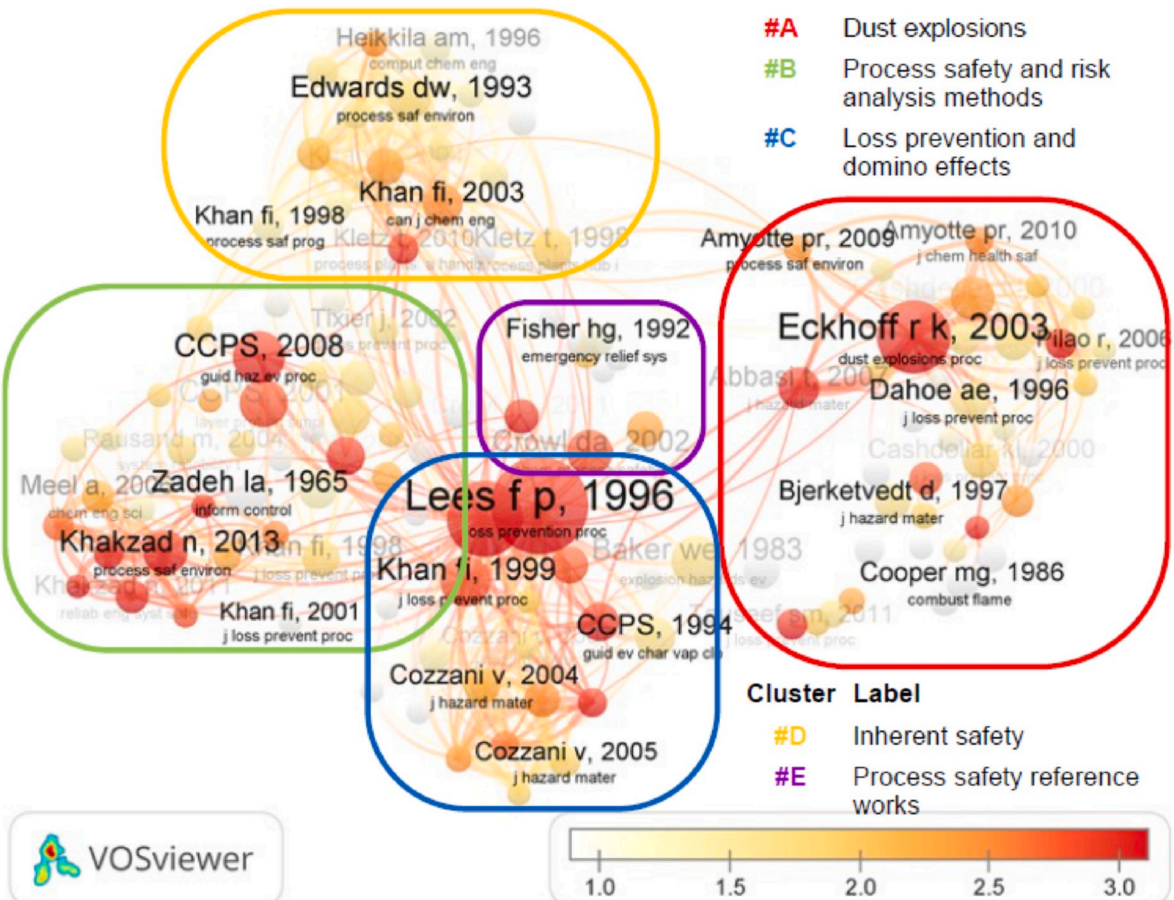


Fig. 13. Co-citation network of highly cited reference clusters based on co-citation strength, with overlay of average annual number of local citations. Node labels indicate first author and publication year, sub-labels indicate the article's source (journals, books or technical report), based on reference list of publications in JLPPI, PSEP, and PSP in the period 1999–2018. The color scale indicates the average number of local citations to an article per year. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

regions contributing to the process safety knowledge domain shows that mainly the developed countries in Europe and North America have laid a foundation for the research field. The USA, the United Kingdom, Italy, and Canada have been the most productive of these countries. Developing countries have been contributing more significantly in recent years, with especially the Peoples Republic of China, India, and Iran becoming important contributors to the research field. In terms of institutions Texas A&M (USA) is by far the largest contributor by number of articles, whereas Memorial University Newfoundland (Canada) and Dalhousie University (Canada) are leading institutions in terms of number of contributions and average impact as measured through number of citations. Several Chinese institutions have been very active in recent years, including China University of Mining & Technology, China University of Petroleum, and Beijing Institute of Technology. TU Delft (the Netherlands), and KU Leuven and University of Antwerp (Belgium) have been active as well in recent years.

A terms co-occurrence analysis has shown that there are three major topic clusters in the process safety research domain: process safety risk management, chemical process safety, and fire and explosion process safety. New research frontiers are being developed in each of these clusters, with the chemical process safety cluster showing most recent activity, and the process safety risk management cluster least. PSEP is active in all topic areas, especially in the recently most active and influential chemical process safety cluster. JLPPI is less active in chemical process safety but has a very strong contribution to the fire and explosion process safety and the process safety risk management clusters. PSP is not very active on chemical process safety, but contains more work on process safety risk management, although then primarily on topics which are recently less at the knowledge frontiers.

An analysis of the intellectual base of the process safety research domain has revealed clusters of journals from where each of these core process safety journals obtain knowledge. This analysis confirms the different focus topics and research profiles of the three journals and identifies *Safety Science* and *Reliability Engineering and System Safety* as the most closely aligned journals on safety risk management. *Journal of Hazardous Materials* is strongly tied with JLPPI and PSEP, whereas several fire and combustion related journals such as *Combustion and Flame*, *International Journal of Hydrogen Energy*, and *Fuel* provide knowledge to especially JLPPI. Several more environmentally focused journals such as *Bioresource Technology*, *Water Research*, *Chemosphere*, *Environmental Science and Technology*, are more closely linked to PSEP. PSP receives most of its knowledge from JLPPI, PSEP, and *Journal of Hazardous Materials*.

Finally, an analysis of highly cited references indicated five dominant clusters, which can be considered as the core intellectual bases of the process safety research field. These clusters concern dust explosions, process safety and risk analysis methods, loss prevention and domino effects, inherent safety, and process safety reference works. All these clusters contain a range of highly influential handbooks, compendia, and authoritative guidelines, which shows that the process safety is a mature research field, where an extensive body of knowledge has been systemized by leading scholars. The clusters also contain various impactful review articles and original research articles which have pushed the boundaries of the respective subdomains. These results, together with insights from the developments in focus topics and journal networks, can also be useful as a basis for making narrative reviews of the research domain or its constituent clusters. Such reviews could provide further detailed insights in the contents of the research articles, further supporting the high-level insights obtained through the presented analyses.

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