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Methods, tools, and framework

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An overview of scientometric mapping for the safety science community: Methods, tools, and framework

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A R T I C L E I N F O

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A B S T R A C T

Scientometrics analysis is increasingly applied across scientific domains to gain quantitative insights in the development of research on particular (sub-)domains of scientific inquiry. By visualizing metrics containing quantitative information about such a domain, scientometric mapping allows researchers to gain insights in aspects thereof. Methods have been developed to answer specific research questions, focusing e.g. on collaboration networks, thematic research clusters, historic evolution patterns, and trends in topics addressed. Several articles applying scientometric mapping to safety-related topics have been published. In context of the Special Issue '*Mapping Safety Science – Reviewing Safety Research*', this article first reviews these, and subsequently provides an overview of key concepts, methods, and tools for scientometric mapping. Data sources and freely available tools are introduced, focusing on which research questions these are suited to answer. A brief tutorial-style description of a scientometrics research process is provided, guiding researchers new to this method how to engage with it. Finally, a discussion on best practices in scientometric mapping research is made, focusing on how to obtain reliable and valid results, and how to use the scientometric maps to gain meaningful insights. It is hoped that this work can advance the application of scientometric research within the safety science community.

1. Introduction

Scientometrics was first introduced by Nalimov and Mul′chenko in 1971 (Nalimov and Mul′chenko, 1971), who defined it as "[the application of] quantitative methods of the research on the development of science as an information process". The term, as a compound of words consisting of "Science" and "Metrics", indicates that measurements of some aspects of science are made. The overall aim of scientometrics research is to gain insights in the development of a scientific research on a specific topic, a broader domain of inquiry, or even the entire scientific body of knowledge. This is approached by mining data about the scientific literature of the topics or other media, often extracted from citation databases and typically focusing on journal articles, papers in conference proceedings, theses, and other types. In the scientometrics research domain, other terms related to scientometrics are used as well, for example bibliometrics (Pritchard, 1969) and informetrics (Nacke, 1979). Together, these are known as the "3-metrics" in the discipline of information and library sciences. However, the terms do not have clear boundaries in practical research, with terms often used interchangeably (Siluo and Qingli, 2017).

Scientometric mapping, as a subdomain of the scientometrics research domain, signifies the application of quantitative methods for understanding and visually representing particular metrics associated with the scientific literature based on bibliographic data. With the development of data science and visualization techniques, scientometric mapping has become an increasingly popular method for reviewing research domains in recent years, also in the safety science community. The combination of data mining and visualization is useful especially for relatively rapidly gaining a high-level understanding of a research domain, its structure in terms of collaboration networks or development history, impactful articles or journals, and topic focus areas. More traditional literature review types have a somewhat different aim, and

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usually focus on the contents of the research articles, summarizing knowledge, identifying gaps and research directions (Grant et al., 2009).

As explained and further elaborated in Section 2, scientometric analysis, and scientometric mapping in particular, has recently become increasingly applied in safety research, several articles that use scientometric methods and tools have been published in the Safety Science. As the overview in Section 2, only a limited range of methods and analysis types have however been applied in this body of safety mapping literature, indicating that the full potential of the scientometric research concepts has not yet been exploited. Moreover, as the technique is relatively recent, many Journal readers and reviewers may not be familiar with the purpose, conceptual basis, methods, tools, and processes of scientometric analysis and mapping. Hence, in context of the Safety Science Virtual Special Issue '*Mapping Safety Science – Reviewing Safety Research*', it is considered valuable to review the application of scientometric mapping in safety research, and to provide an overview of some key concepts, methods, and tools of scientometrics and scientometric mapping to advance the application of the techniques. Thus, this article aims to review the application of scientometric analyses in safety research, and to serve as a tutorial to the approaches, enabling high-quality applications and analyses.

The remainder of this article is organized as follows. Section 2 reviews the use of scientometrics and scientometric mapping in safety research, showing the range of safety topics addressed, and indicating some common limitations and methodological shortcomings in the published research. Section 3 provides an overview of scientometrics concepts, data sources, and of available methods and tools for performing scientometric mapping analysis. Section 4 serves as an introductory tutorial, describing a generic framework of practically performing a scientometric mapping analysis. In Section 5, a discussion is made, focusing on common pitfalls and best practices. Section 6 concludes.

2. Overview of scientometric mapping applications in safety research

As already indicated, recently, the application of scientometric mapping methods to safety science related research has become increasingly popular. To identify safety-related articles utilizing scientometric mapping, a literature search was performed initially in August 2018 and updated during the review process in October 2020, using the Web of Science citation, Scopus, ScienceDirect and SpringerLink database with the following terms: "VOSviewer", "CiteSpace", "bibliometric", "scientometric", "safety" or "accident*" or "disaster*". Based on this search, the authors collected 62 papers with topics related to safety and scientometric mapping, which are listed in Table 1. Of these, 44 papers (71%) were published in the past three years (2018–2020), with in total 15 articles (24%) related to scientometric mapping published in the journal *Safety Science* in the past five years, of which 11 articles in the past two years. This indicates the interest shown in the safety research community to use scientometrics tools to gain insights in literature.

As seen in Table 1, nearly all of the papers address application-oriented research domains, and focus on particular safety related research topics. For instance, Huang et al. (2020) focus on failure mode and effect analysis, Orimoloye et al. (2020) on technology in disaster risk management, Yang et al. focus on universities laboratory safety (Yang et al., 2019b), Luo and Shin on maritime accidents (Luo and Shin, 2019), Jin et al. on construction safety (Jin et al., 2019), and Amin et al. on process safety and risk (Amin et al., 2019a). Some authors have used the scientometric mapping approach to gain insight in wider safety principles, with e.g. Goerlandt et al. (2020) focusing on risk communication, van Nunen et al focusing on safety culture (van Nunen et al., 2018), and Patriarca et al. (2018) on resilience engineering. Scientometrics has also been used to provide insights in aspects of the *Safety Science* journal as a knowledge carrier in safety research (Merigó et al., 2019), and to identify safety journals (Li and Hale, 2015) and topic maps of core safety journals (Li and Hale, 2016). This shows the versatility of the research methods and tools to answer a range of research questions, spanning a diverse range of topics and a varying scope of the covered research domain. Recently, scientometrics has also been used to compare the scope and focus topics of process safety related journals (Li et al. 2020a), and to obtain insights in the legacy of key safety researchers such as Trevor Kletz (Li et al. 2020b) and Sam Mannan (Li et al. 2020c).

From the list of articles using scientometric mapping in safety research in Table 1, it is evident that most of the research is performed using relatively simple descriptive statistics and basic scientometric mapping tools. Mostly, only one or few software tools were applied in a given article. Web of science and Scopus were two widely used databases in mapping safety research. VOSviewer, CiteSpace and BibExcel are commonly applied in research, with VOSviewer the most frequently used software among these. Compared to other tools, VOSviewer is a relatively easy and accessible scientometric mapping tool, which has been developed not only for the core scientometric community, but also for use by interested researchers in other scientific domains, see the list of VOS viewer publications in https://www.vosviewer.com/publications.

Apart from the relatively small range of tools used (and corresponding insights achieved), there are also a few problems apparent in some applications of scientometric mapping to safety related topics. For example, in several articles, the data retrieval process is not clear, which nevertheless is an essential issue also in traditional review articles (Wee and Banister, 2016). Moreover, some articles provided quite little interpretation of the scientometric mapping results. In scientometric research, valuable insights can be gained in the development of a research field, collaborations, and trends, beyond a simple description of mapping visualizations resulting from the software application. This however requires commitment to exploring the results, at least some experience with the research domain, and a creative and critical approach to interpreting the visualizations. The most prevalent problem is that many articles listed in Table 1 lack a data normalization step in the analysis process. For instance, similar terms are not merged (e.g., behavior and behaviour, accident and accidents, AHP and Analytic Hierarchy Process), and/or ambiguities and alternate spelling of authors' names in the databases were processed in the software without disambiguation (e.g., Hale Andrew and Hale AR refer to the same author, and the corresponding records should be merged in authors analysis). Without data normalization, important patterns may be left unnoticed, and biased or even erroneous results may be obtained.

3. Scientometrics mapping: An overview

In this Section, a brief overview is given of the methods, data sources, tools, and techniques proposed and commonly applied in the scientometric research community. The intention is to provide an introductory description, to facilitate understanding of the main ideas and approaches by readers having little or no experience with performing or interpreting scientometric analyses, or reading articles showing its results. Section 3.1 outlines common methods in scientometric mapping, focusing on some basic concepts and the kind of questions which these methods are suited to answer. Section 3.2, some popular available data sources to perform scientometric analyses are introduced. In Section 3.3 provides an overview of a range of freely available tools for scientometric mapping, aiming to facilitate safety researchers interested in performing analyses in the identification and selection of suitable tools for their purposes. Finally, Section 3.4 introduces normalization and clustering in scientometric mapping, which are important techniques to facilitate interpretations of scientometric mapping analyses.

Table 1
Articles approaching safety related topics using scientometric mapping.

No.	Author (year)	Research topics	Journal	Software used	Database used
1	(Alkaissy et al., 2020)	Construction safety management	Safety Science⋆	VOSviewer	Scopus, WOS
2	(Bamel et al., 2020)	Safety climate	AAP	VOSviewer	Scopus
3	(Du et al., 2020)	Disaster emergency management	NH	VOSviewer	Scopus
4	(Feng and Cui, 2020)	Disaster emergency response	NH	VOSviewer	WOS
5	(Gil et al., 2020)	Shipboard DSS for accident prevention	Safety Science⋆	VOSviewer, bibliometrix	WOS
6	(Goerlandt et al., 2020)	Risk communication	IJERPH	VOSviewer, CiteSpace	WOS
7	(Haghani et al., 2020)	Coronavirus and COVID-19 safety	Safety Science⋆	VOSviewer	Scopus
8	(Huang et al., 2020)	Failure mode and effect analysis	RESS	CiteSpace	WOS
9	(Kulkarni et al., 2020)	Waterway risk management	Safety Science⋆	VOSviewer	WOS
10	(Li et al., 2020a)	Process safety journals	JLPPI	VOSviewer	WOS
11	(Li et al., 2020b)	Trevor Kletz' scholarly legacy	JLPPI	CiteSpace	WOS
12	(Li et al., 2020c)	Sam Mannan's work on process safety	JLPPI	VOSviewer	WOS
13	(Liang et al., 2020)	Construction safety management	IJOSE	HistCite	WOS
14	(Lima and Bonetti, 2020)	Coastal community vulnerability to extreme events	NH	VOSviewer, Bibliometrix	Scopus
15	(Liu et al., 2020)	Pool fires	JLPPI	VOSviewer, CiteSpace	WOS
16	(Orimoloye et al., 2020)	Technology in disaster risk management	ESPR	Rstudio, Bibliometrix	WOS
17	(Patriarca et al., 2020)	Human reliability analysis	RESS	VOSviewer, PowerBi	Scopus
18	(Sarkar and Maiti, 2020)	Machine learning in occupational accident analysis	Safety Science⋆	VOSviewer	Scopus
19	(Tao et al., 2020)	Human reliability	JCP	VOSviewer	WOS
20	(Yang et al., 2020)	Process safety in China	JCP	VOSviewer	WOS
21	(Zhang et al., 2020)	Seismic risk	Safety Science⋆	Not mentioned	WOS
22	(Zhu et al., 2020)	Healthcare worker's occupational health	IJERPH	CiteSpace	WOS
23	(Zou et al., 2020)	Accident analysis & prevention journal analysis	AAP	VOSviewer, CiteSpace	WOS
24	(Akram et al., 2019)	Construction safety	Safety Science⋆	VOSviewer, Gephi	WOS, Scopus
25	(Amin et al., 2019a)	Process safety and risk	PSEP	VOSviewer	WOS, Scopus
26	(Amin et al., 2019b)	Process system failure, reliability	EFA	VOSviewer	WOS, Scopus
27	(Ellis et al., 2019)	Resilient health care	Safety Science⋆	Gephi	WOS
28	(García-Gámez et al., 2019)	Clinical safety	NO	VOSviewer	PubMed, WOS
29	(Jin et al., 2019)	Construction safety research	Safety Science⋆	VOSviewer	Scopus
30	(Luo and Shin, 2019)	Maritime accidents	AAP	Not mentioned	Not mentioned
31	(Merigó et al., 2019)	Safety science journal analysis	Safety Science⋆	VOSviewer	WOS
32	(Sweileh, 2019)	Natural disasters, health-related	HRPS	VOSviewer	Scopus
33	(Yang et al., 2019a)	Landslide	JMS	CiteSpace	WOS
34	(Yang et al., 2019b)	Universities laboratory safety	Safety Science⋆	VOSviewer	WOS
35	(Gao and Ruan, 2018)	Coastal flooding	CGS	BibExcel, Pajek	WOS
36	(Gobbo et al., 2018)	Process safety, industry 4.0	PSEP	VOSviewer	WOS
37	(Liang et al., 2018)	Construction safety management	IJOSE	CiteSpace	WOS
38	(Lim et al., 2018)	Maritime risk	AOR	Not mentioned	Not mentioned
39	(Patriarca et al., 2018)	Resilience engineering	Safety Science⋆	Not mentioned	Scopus
40	(Sharma et al., 2018)	Road traffic injuries	HRPS	VOSviewer	Scopus
41	(Shen et al., 2018)	Natural disaster	PLOS One	CiteSpace	WOS
42	(van Nunen et al., 2018)	Safety culture	Safety Science⋆	VOSviewer	WOS
43	(Zhang et al., 2018)	Disaster management policy	IJDRS	Not mentioned	pkulaw database
44	(Zou et al., 2018)	Road safety studies	AAP	VOSviewer, SCI2	WOS
45	(Li et al., 2017)	Domino effects	JLPPI	VOSviewer, CiteSpace	WOS
46	(Rajagopal et al., 2017)	Supply chain risk	CIE	BibExcel, Gephi	Not mentioned
47	(Wears, 2017)	Rasmussen research	AE	HistCite, R	Google Scholar, WOS
48	(Beerens and Tehler, 2016)	Disaster exercise evaluation	IJDRR	MATLAB, VOSviewer	WOS, Scopus
49	(Hosseini et al., 2016)	System resilience	RESS	CiteSpace	WOS
50	(Huai and Chai, 2016)	Water security	Scientometrics	Not mentioned	WOS
51	(Li and Hale, 2016)	Topic map of safety journals	Safety Science⋆	VOSviewer	WOS
52	(Nascimento and Alencar, 2016)	Natural disasters	JLPPI	VOSviewer	WOS, Scopus
53	(Mryglod et al., 2016)	Chornobyl disaster	Scientometrics	VOSviewer, Pajek	Scopus
54	(Gall et al., 2015)	Disaster risk	IJDRR	VOSviewer, HistCite	WOS
55	(Li and Hale, 2015)	Identification of safety journals	Safety Science⋆	VOSviewer	WOS
56	(Mesdaghinia et al., 2015)	Microbial risk assessment	Scientometrics	VOSviewer	Scopus
57	(Wu et al., 2015)	Landslides research	Landslides	UCINET, CiteSpace	WOS
58	(Hagenzieker et al., 2014)	Road safety research	TRP-F	——	Scopus
59	(Rodrigues et al., 2014)	Patient safety	BMJ Open	VOSviewer	Scopus
60	(Liu et al., 2012)	Earthquake	Scientometrics	VOSviewer, Net draw	WOS
61	(Chen, 2006)	Terrorism analysis	JASIST	CiteSpace	WOS
62	(Stelfox et al., 2006)	Patient safety	QSHC	Not mentioned	MedLine

Note: AAP = Accident Analysis & Prevention | AE = Applied Ergonomics | AOR = Annals of Operations Research | CGS = Chinese Geographical Science | CIE = Computers & Industrial Engineering | EFA = Engineering Failure Analysis | ESPR = Environmental Science and Pollution Research | HRPS = Health Research Policy and Systems | IJDRR = International Journal of Disaster Risk Reduction | IJDRS = International Journal of Disaster Risk Science | IJERPH = International Journal of Environmental Research and Public Health | IJOSE = International Journal of Occupational Safety and Ergonomics | JASIST = Journal of the American Society for Information Science and Technology | JCP = Journal of Cleaner Production | JLPPI = Journal of Loss Prevention in the Process Industries | JMS = Journal of Mountain Science | NH = Natural Hazards | NO = Nursing Outlook | PPI = Prevention in the Process Industries | PSEP = Process Safety and Environmental Protection | QSHC = Quality and Safety in Health Care | RESS = Reliability Engineering & System Safety | Transportation Research Part F = TRP-F | WOS = Web of Science | ⋆papers published in Safety Science.

3.1. Methods for scientometric mapping

Several scientometric methods have already been applied to scientometric mapping, see in Fig. 1 (Morris and Van der Veer Martens, 2008). These for instance include co-authorship analysis, co-words analysis and co-occurrence analysis, which will be introduced below. All the techniques shown in the figure are relation-based analyses, and can be divided into three broad categories: citation relations, words co-occurrence, and co-authorship relations (van Eck and Waltman, 2014b). More detailed information for each method is provided in Table 2.

Constituting the first category of scientometric mapping methods, **citation relations methods** construct a knowledge unit matrix based on their citations and provide an understanding of how articles in a body of literature relate to each other when taking citations as a metric of interest. There are three commonly applied citation relations-based methods: the direct citation analysis, the bibliographic coupling and the co-citation analysis, see Fig. 2.

The **direct citation analysis (DCA)**, also known as inter-citation or cross citation, shows the direct citing relationships between articles, without creating the connection based on the third-party paper (Yang and Wang, 2015). Fig. 2(a) shows an example of a direct citation network, where paper P3, P4, P5 are cited by P1 and P2. In the scientometric research area, P1 and P2 are known as “citing papers”, and P3, P4 and P5 as “cited papers”. Several tools have been developed for DCA, for example HistCite (Garfield et al., 2002) and CitNetExplorer (van Eck and Waltman, 2014a). These tools can easily be applied to create direct citation networks and to analyse the history (Garfield, 2009), evolution (Wu et al., 2017) and research front (Bornmann and Marx, 2012)of the research domain.

Bibliographic coupling (BC) was first introduced by Kessler in 1963 (Kessler, 1963), to measure overlap of references to literature between two or more articles. For example, in Fig. 2(b), paper P1 and P2 cite the same publications (P4 and P5) in their reference list, so that there is a bibliographic coupling between these articles. The coupling strength of the two articles is determined by the number of cited publications they share. The higher the coupling strength, the stronger the relation between these citing articles. In Fig. 2(b), the coupling strength between P1 and P2 is two. The similarity idea of bibliographic coupling method has been extended to authors (Zhao and Strotmann, 2008a), and also can be applied to Journals (Small and Koenig, 1977), institutes, countries/regions analysis (Glänzel and Czerwon, 1996). Based on the bibliographic coupling theory, the evolution of research activities and intellectual influences (Zhao and Strotmann, 2008b), research front (Jarneving, 2007) and intellectual structure (Park and Jeong, 2013) and other practice of interest, can be analysed for a certain topic or domain such as safety research.

Document Co-citation was introduced by (Small, 1973) and (Marshakova-Shaikevich, 1973), and is defined as two publications which are cited together in one article. For example, in Fig. 2(a), P3 and P4 are together cited by P2, which means that P3 and P4 are co-cited. If two articles were frequently co-cited, it means that they are highly related. The original co-citation strength of two articles can be measured by the number of citing articles. In Fig. 2(a), articles P4 and P5 are co-cited by P1 and P2, so that the co-citation strength between P4 and P5 is 2, see in Fig. 2(c). With the development of the co-citation analysis, also other units of analysis can be focused on, i.e. not only for documents co-citations, but also for authors (White and Griffith, 1981), or journals (Ding, 2000). Compared with bibliographic coupling, the co-citations strength was changed overtime, while the bibliographic coupling strength is fixed after two papers published. It means that bibliographic coupling is retrospective whereas co-citation is essentially a forward-looking perspective (Garfield, 2001). The document co-citations analysis can be used to analyse the intellectual base (Culnan, 1987), intellectual structure (Pilkington and Meredith, 2009; White and Griffith, 1981), invisible colleges (Casey and McMillan, 2008; McMillan, 2008) and also the research front (Boyack and Klavans, 2010) in a scientific domain.

The second category of scientometric mapping methods, **co-word analysis (also called word co-occurrence analysis)**, was proposed by (Callon et al., 1983) as a content analysis technique that is effective in mapping the strength of association between items in textual data (Wang et al., 2012). The construction of the co-word network is based on the number of co-occurrence of two words appearing in the same documents, abstracts or keywords unit. By measuring the strengths of the word co-occurrence links, co-word analysis can reveal and visualize the interactions between research topics (Leung et al., 2017). Co-word analysis is widely used for knowledge discovery (He, 1999), “hot” topics and research trends (An and Wu, 2011; Leung et al., 2017) in the analyzed scientific domain.

The third category of scientometric mapping methods concerns **co-authorship analysis**. Collaboration has become very common in scientific communities (Wuchty et al., 2007), and it has also become one of the important focus areas in scientometric mapping analyses. An authors' collaboration network reflects the social connections of the researchers in the area, but moreover provides insights in the social structure of the science domain. In the scientometric analysis, two authors have collaborated if they co-authored papers. Three levels have been distinguished in co-authorship analysis (Glänzel, 2002): micro level (authors analysis), meso level (institutes or cities analysis), and macro level (countries/regions analysis). The authors analysis can show who the highly productive authors are in a scientific domain of inquiry, and how authors are socially connected and collaborate with each other through article co-authorship relations (Melin and Persson, 1996). Similarly, meso and macro level analysis provide such insights for institutions/cities and countries/regions, showing active contributors and how these are connected.

3.2. Data sources for scientometric mapping

There are several bibliographic data sources which can be applied in scientometric mapping research. These include the abstract and citation index databases such as Web of science and Scopus, the full text databases such as ScienceDirect, SpringerLink, and ProQuest, the free online database sources such as Google Scholar, Microsoft Academic, Dimensions, and PubMed, and other data sources including Patent-Derwent innovations index, BOOK Citation index, and others. Among these databases, Web of Science and Scopus are the most widely used ones in scientometric mapping research. These two databases are commercial (subscription-based) bibliographic databases, with a higher data quality than other comparable databases. These two databases can be recommended for beginning users of scientometric mapping.

Web of Science (WOS) was founded by Eugene Garfield in the 1960s and currently owned by Clarivate Analytics. The Web of Science platform has integrated several bibliographic databases, with nearly 33,000 + science/social science/ arts and humanities journals having been indexed in the database since 1900[1]. Compared with other databases, WOS has played an important role in the history of scientometric analysis, and has had a profound effect on the evolution of scientometric research, by making literature searches easier and more comprehensive.

Scopus is a comparatively recently developed citation database. Launched in 2004 by Elsevier, it has covered more journals than that of Web of Science (Burnham, 2006), while the quality of the bibliographic data from Scopus is somewhat lower than Web of Science. Through further developments, the data quality of Scopus has improved in recent years and has increasingly become more popular in the scientific community.

Fig. 3 displays search interest of the terms ‘Web of Science’ and ‘Scopus’ in the Google search engine, performed on 30 August 2019. It clearly demonstrates that Scopus has attracted more interest than WOS

[1] https://clarivate.com/products/web-of-science/.

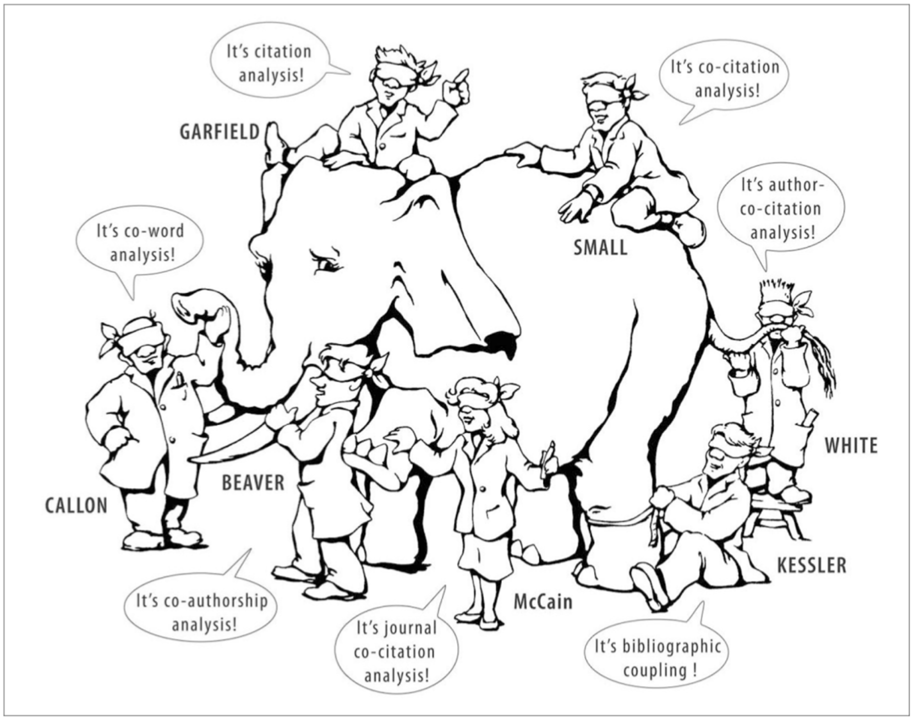


Fig. 1. Methods applied in scientometric mapping (Morris and Van der Veer Martens, 2008).

Table 2
Key methods for scientometric mapping.

No.	Knowledge unit	Sub-knowledge unit	Co-authorship	Co-occurrences	Co-citations	Bibliographic coupling	Direct citations
1	Authors	Citing author	✓	——	×	✓	×
		Cited author	×	——	✓	×	×
2	Institutions	——	✓	——	×	✓	×
3	Regions/Countries	——	✓	——	×	✓	×
4	Journals	Citing Journal	×	——	×	✓	×
		Cited Journal	×	——	✓	×	×
5	Categories	——	×	✓	×	✓	×
6	Keywords	Authors keywords	×	✓	×	×	×
		Keywords Plus	×	✓	×	×	×
7	Terms	Titles/Abstract/keywords	×	✓	×	×	×
8	Articles	Citing articles	×	——	×	✓	✓
		Cited articles	×	——	✓	×	✓

Note: ✓Methods can be used for knowledge unit analysis.

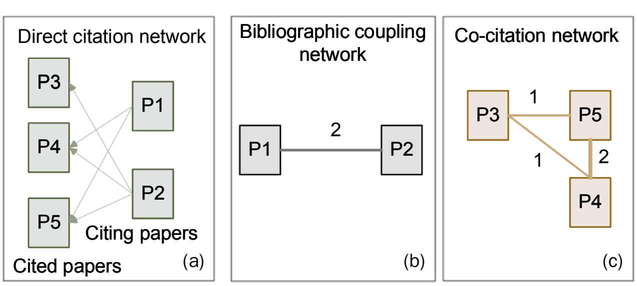


Fig. 2. Direct citation network, bibliographic coupling network and co-citation network of papers.

during the past 5 years.

Almost all bibliographic databases include authors, addresses (Institutions, cities or Countries/regions), keywords and abstract, while the bibliographic data of Web of Science and Scopus have more detailed information than other databases, especially citations data. The typical content of the bibliographic data is show in Fig. 4.

3.3. Tools for scientometric mapping

The development and application of tools for scientific research can help researchers improve their research efficiency, and speed up discovery, innovation, and information exchange processes. The development of research instruments or tools has been regarded as a key characteristic of the second stage on the evolution of scientific disciplines (Shneider, 2009). Currently, there are multiple tools which can be applied in scientometric mapping analysis. Some of these are general statistical, network analysis or visualization tools, while others are specifically developed for performing scientometric mapping analyses. An earlier review of tools for scientometric mapping has been presented by Cobo et al. (2011) and van Eck and Waltman (2014b). In the following, the overview of available tools is updated and extended in comparison with these reviews (Cobo et al., 2011; van Eck and Waltman, 2014b).

At the beginning stage of the scientometrics mapping research area, just a handful of tools were available for scientometric mapping. At that time, scientometric analysis results were always visualized using generic visualization software, after statistical analysis of bibliometric data was

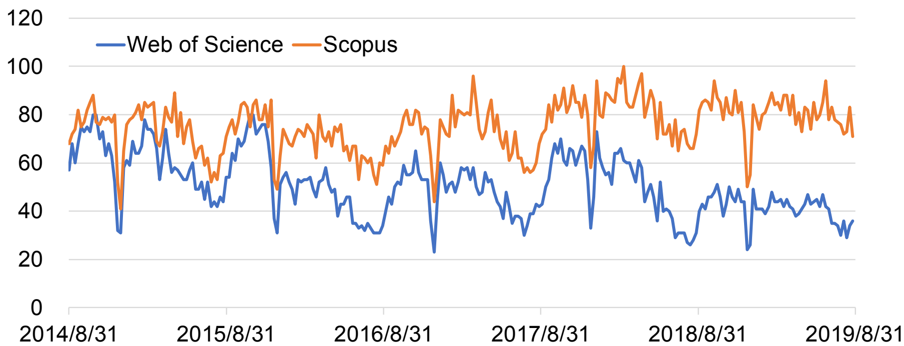


Fig. 3. Google search trends of 'Web of Science' (blue) and 'Scopus' (orange) databases in the past five years. The data is obtained from Google Trends on 2019–08-30, anyone can visit the Online figure: https://trends.google.com/trends/explore?q=web%20of%20science,scopus&date=today%205-y#TIMESERIES Interest over time (from Google): Numbers represent search interest relative to the highest point on the chart for the given region and time. A value of 100 is the peak popularity for the term. A value of 50 means that the term is half as popular. A score of 0 means there was not enough data for this term.

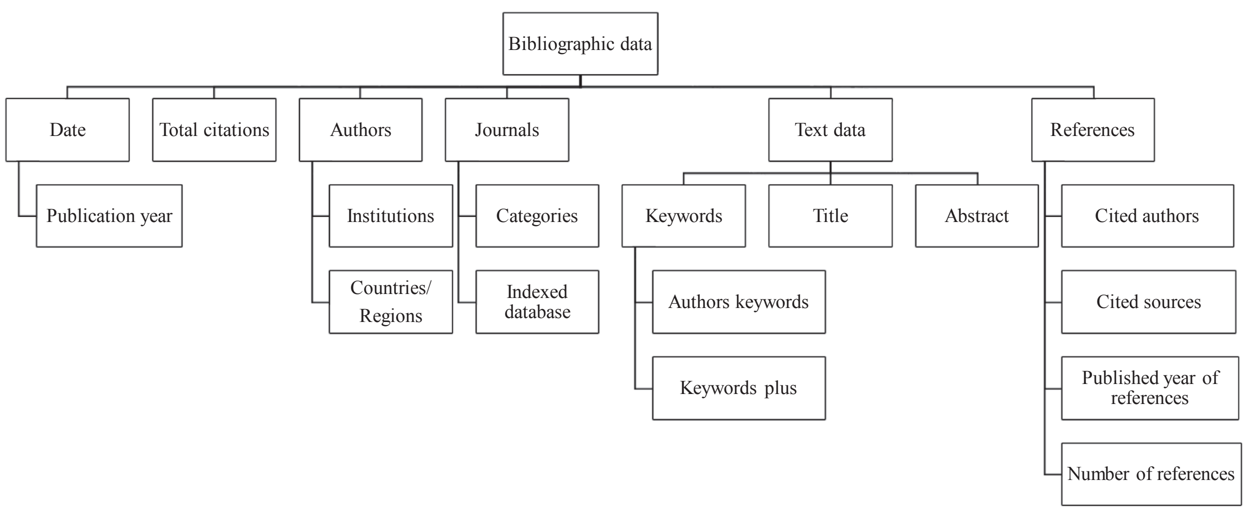


Fig. 4. Key content of bibliographic data.

completed. For example, Pajek (Nooy et al., 2018), Netdarw, Gephi (Bastian et al., 2009), SPSS and UCINET (Borgatti et al., 2002) have been widely used to perform bibliographic statistical analysis, and especially for visualizing the results. After the year 2000, some researchers from the mathematics and computer science disciplines have joined the scientometric community, which facilitated the development of specific tools for scientometric mapping.

Currently, there are more than 25 tools available specifically for scientometric mapping purposes (Li, 2017). These tools can be divided into three categories: local-based tools, web-based tools, and computer language-based tools. Local-based tools concern software which must be installed on a local computer or computer networks. Several popular tools were developed in this way, for example BibExcel, CiteSpace, and VOSviewer. Web-based tools work so that a user should first upload the data to an online server, after which this data is analysed online. With computer language-based tools is meant here that some packages which have already been developed for scientometrics mapping analysis, can be used with general-purpose softwares such as R, Python, or Matlab. These tools allow reading and analysing the data easily, where in some packages the user needs to access and revise parts of the code to perform a specific analysis in his or her research.

Comparing these three types, the web-based tools are generally the easiest to apply, whereas the computer language-based are the hardest. Local-based tools require some familiarization with the functionalities of the software, but are mostly rather intuitive and easy to use. The authors suggest that beginners start with a demo dataset, apply this to a web-based tool, and try to understand the scientometric mapping processes and interpret the basic results. More advanced users aiming to perform scientometric research e.g. on a safety-related topic, and aiming to publish the results in conference proceedings, journals, theses, or books, are advised to invest in learning selected local-based tools, appropriate to the intended research aims of the scientometric analysis and mapping. This is because web-based tools always lack data cleaning and pre-processing functions, at least in currently available implementations of the tools. As indicated in Section 2, this can lead to results being unreliable or biased, and it usually also complicates interpreting the results. Computer language-based tools, while sometimes providing powerful functionalities for more advanced analyses, are more difficult to use, and are not advised for beginners.

A list of scientometric mapping tools has been done by (Li, 2017, 2018a, b; Li and Chen, 2016). After inspection, these are categorized in the three categories described above. The results are shown in Table 3.

In the current paper, based on the above identified tools and previous experiences with the tools (Li, 2017, 2018a, b; Li and Chen, 2016; Li et al., 2018), eight local-based tools are selected for a deeper introduction. This aims to provide readers some more insight in what these tools are, and what functionalities these have. Basic information of each tool is listed in Table 4.

The **BibExcel**[2] software is included in the first group, see Table 4. BibExcel was developed by Prof. Emer. Olle Persson from Umeå University. This tool applied ideas from MS Excel, whereas results obtained from BibExcel can be opened, edited, and analyzed using MS Excel. The matrix or the network file can also be loaded into SPSS, UCINET or Pajek for in-depth analyses, for example, multidimensional scaling (MDS) or Principal Component Analysis (PCA). BibExcel has no functions for data

[2] BibExcel: https://homepage.univie.ac.at/juan.gorraiz/bibexcel/.

Table 3
Categories of freely available tools for scientometric mapping.

No.	Tool categories	Specific tools for scientometric mapping
1	Local- based	BibExcel (Persson et al., 2009) CiteSpace (Chen, 2006) CitNetexplorer (van Eck and Waltman, 2014a) CRExplorer (Thor et al., 2016) HistCite (Garfield, 2004) Publish or Perish (Harzing, 2010) SCI2 (Light et al., 2014) SCIMAT(Cobo et al., 2012) VOSviewer (van Eck and Waltman, 2010)
2	Web-based	Nails-HAMMER (Knutas et al., 2015) RPYS i/o (Comins and Leydesdorff, 2016) Tree of Science (Botero et al., 2018) biblioshiny(Aria and Cuccurullo, 2017) Web version of Bibliometrix(R) Map Equation (Rosvall et al., 2009) VisualBib (Dattolo and Corbatto, 2019) NETSCITY (Maisonobe et al., 2019).
3	Computer language-based	BibliTools(Python) (Grauwin and Jensen, 2011) Metaknowledge(Python) (McLevey and McIlroy-Young, 2017) Bibliometrix(R) (Aria and Cuccurullo, 2017) ScientoPy(Python) (Ruiz-Rosero et al., 2019)

visualization, but the software can generate files for subsequent visualization in Pajek, Gephi, or VOSviewer. The most important advantage of BibExcel is the transparency of the data processing, where results can be obtained in each step. A disadvantage is that data processing is somewhat more complicated in BibExcel, compared to other tools.

BibExcel can be considered as one of the most important tools in the scientometric mapping community, having had a high influence particularly at the beginning stage of scientometric mapping research. BibExcel is a pioneering tool which is freely available and has good fame in the community[3]. As observed by its developer: “half of my fame is from writing and the other half from programming” (MEYER and NZEL, 2012).

CiteSpace[4], VOSviewer[5], SCI of SCI tool[6], and SCIMAT[7] constitute the second group of tools for scientometrics mapping in the list of Table 4. These tools are similar in that these all have advanced functions for analysing and visualizing science domains. Each of these tools are highly regarded as general-purpose scientometrics mapping tools inside the scientometrics research community.

CiteSpace stands for ***Citation Space***, and it was developed by Prof. Chaomei Chen from Drexel University (USA) in 2003, and released in 2004. The tool is developed for visualizing patterns and trends in scientific literature, inspired by Tomas Kuhn’s theory of the structure of scientific revolutions (Kuhn, 1962), especially ideas of paradigm shifts within scientific communities (Chen, 2016). The special and important function of CiteSpace is to map the dynamic reference co-citations network, with the combination of the citations burst detecting (Kleinberg, 2003), turning points identification (Chen, 2004), network clustering and clusters labelling techniques (Chen et al., 2010). CiteSpace is the most widely used tool for scientometric mapping, with currently (August 2019) 425 published articles having applied CiteSpace for scientometric mapping related research (see Table 4).

VOSviewer stands for ***visualization of similarities***, and it was developed by Dr. Nees Jan van Eck and Prof. Ludo Waltman in 2009, from Leiden University’s Centre for Science and Technology Studies (CWTS). The tool is developed for mapping and clustering the landscapes of the scientific domains by using the bibliographic data from different sources, including Web of Science, Scopus, and Dimension. A special feature of VOSviewer is the application of a unified approach to mapping networks, and inclusion of clustering methods in the scientometric network analysis (Waltman et al., 2010). Supported network types include co-author networks, co-citation networks, and bibliographic coupling and citation networks analysis. Moreover, VOSviewer can also be applied to identify noun phrases from title and abstract of the scientific documents, using text mining algorithms (van Eck et al., 2010). Compared with other tools, VOSviewer can easily visualize maps of even large scientific domains, and handle large datasets (van Eck and Waltman, 2010). Currently, there are 321 articles (See Table 4) listed in Scopus which have used VOSviewer for scientometric mapping related research. VOSviewer can thus be considered a new emerging tool for scientometric mapping.

The **SCI2** tool (which stands for ***science of science*** tool) was developed by SCI2 team, which includes Prof. Katy Börner and Dr. Kevin W. Boyack, and constitutes of researchers mainly from the Cyberinfrastructure for Network Science Center and the Department of Information and Library Science at Indiana University. The main function of this tool is supporting analyses trying to answer research questions addressing temporal (when), geospatial (where), topical (what), and network (with whom) aspects of a scientific domain of inquiry. Different levels of analysis are supported: from micro to macro in science of science research (Light et al., 2014). SCI2 is a modular-based and open source software, with features allowing new functions to be easily plugged in into the main software by other developers.

SCIMAT (Science Mapping Anaylsis Tool) is developed by the Sci^{2}s research group at the University of Granada in Spain. It is an open source software tool for performing a science mapping analysis under a longitudinal framework (Cobo et al., 2012), and it also can be used to easily create the strategic diagram and evolution map. The open source code of SCIMAT makes it convenient to revise and update. Finally, SCIMAT has powerful data pre-processing and data disambiguation functionalities.

The third group of the tools included in Table 3 includes three tools. These distinguish themselves from other tools as the objective of these tools is to analyse and identify historical patterns of scientific domains, focusing on the documents level. Thus, the tools can be used to answer research questions concerning which articles have made significant impacts in the development of a research domain, and how these articles relate to one another. Among the tools, CitNetExplorer can be regarded as a new generation implementation of the HistCite software.

HistCite (History of cite) software is an implementation of algorithmic historiography, and is widely used for generating chronological citations networks based on bibliographic data from Web of Science. It was developed by Dr. Eugene Garfield in 2001, and has been released in 2007[8]. Dr. Eugene Garfield also created, amongst other, the Web of Science database, and has been widely regarded as one of the ‘fathers’ of scientometrics and a scientific information pioneer[9].

In 2014, Dr. Nees Jan van Eck and Prof. Ludo Waltman from Leiden University developed the more advanced **CitNetExplorer** tool for creating citation links between high cited articles. CitNetExplorer, which stands for *Citation Network Explorer*, can be applied to study the development of a research filed, to delineate the literature on a research topic, and especially for supporting more in-depth and contents-focused literature reviews. CitNetExplorer has more advanced functions than HistCite: for example, it can identify clusters, core papers, and main development paths in the citation network. Advanced functions for interactive inspection of the network furthermore enable in-depth

[3] For his contribution in scientometric research, Prof. Emer. Olle Persson was awarded the Derek de Solla Price Medal in 2011.
[4] CiteSpace: https://sourceforge.net/projects/citespace/.
[5] VOSviewer: https://www.vosviewer.com/.
[6] SCI2: https://sci2.cns.iu.edu/user/welcome.php.
[7] SCIMAT: https://sci2s.ugr.es/scimat/.
[8] Nancy K. Herther. Eugene Garfield Launches HistCite. Posted on October 29, 2007.http://newsbreaks.infotoday.com/NewsBreaks/Eugene-Garfield-Launches-HistCite-40024.asp
[9] For his contribution in scientometrics, he also awarded the first Derek de Solla Price Medal in 1984.

Table 4
Selected popular freely available tools for scientometric mapping.

Groups	No.	Tools	Developer	Institutions	Country	YR/D	Last version	NPS
A	1	Bibexcel	Olle Persson	Umeå University	Sweden	——	2016–2-20	74
B	2	CiteSpace	Chaomei Chen	Drexel University	USA	2003	5.4. R4	425
	3	VOSviewer	Van Eck, N. J	Leiden University	The Netherlands	2009	1.6.11	321
	4	SCI2	Sci2 Team	Indiana University	USA	2009	v1.3	33
	5	SCIMAT	M.J. Cobo et al	University of Granada	Spain	2012	v1.1.04	33
C	6	HistCite	Garfield E	Thomson Reuters Sci	USA	2004	12.03.17	106
	7	CitNetExplorer	Van Eck, N. J	Leiden University	The Netherlands	2014	1.0.0	13
	8	CRExplorer	Andreas Thor	HfT-Leipzig	Germany	2016	1.9	9

Note: Developer here means first developer or leader of the software develop. YR/D = Year developed/released; last version was search on May 2019. NDS = Number of papers in Scopus, the number of documents of each software was retrieved from Scopus database by using the topic (Article title, Abstract, Keywords) search of the name of software.

analyses of the citation network (van Eck and Waltman, 2014a).

CRExplorer stands for ***Cited References Explorer***, and is a software which was developed by Prof. Andreas Thor from the University of Applied Sciences for Telecommunications Leipzig (HfTL). Its content was developed by Dr. Lutz Bornmann from the Max Planck Society, and Dr. Robin Haunschild from the Max Planck Institute. The software has received further support from Prof. Emer. Loet Leydesdorff, Dr. Werner Marx and Dr. Rüdiger Mutz. The main function of the tool is for reference publication year spectroscopy (RPYS) with cited references standardization. This is a new technique implemented in the CRExplorer tool, to support identification of milestones in a research domain (Comins and Leydesdorff, 2017). CRExplorer can also be used for the historical roots analysis of a domain (Marx et al., 2014).

3.4. *Matrix normalization, mapping and clustering in scientometric mapping*

There are several normalization methods which have been used to measure the similarities of the items (e.g. authors, keywords and references etc.) in the scientometric mapping. These can be divided into two types: set-theoretic measures and probabilistic measures (Eck and Waltman, 2009). For example, cosine, inclusion index and Jaccard index are set-theoretic measures, while the association strength is the probabilistic measure (see Table 5). Different tools include pre-set preferences for applying selected similarity measures. In CiteSpace, the cosine method is the default similarity measure, while the Jaccard and dice index are alternative methods. In VOSviewer, the association strength is the default similarity measure, with fractionalization an alternative included in the software. Detailed information concerning the similarity measures included in each tool is listed in Table 6.

After the normalization of the raw co-occurrence matrix, mapping and clustering can be conducted. The PCA (principle component analysis), MDS (multidimensional scaling) and VOS (Similar as MDS method) are used to transform the matrix into a two-dimension space, and the euclidean distance is always used to show the similarities between each knowledge unit, and it was named as distance-based map. In recent years, network mapping methods have become popular in scientometric research communities. In this method, knowledge units are still mapped into a 2-dimension space, with the link strength being used to show the similarities of each unit. Such maps are thus a kind of graph-based map. After locating the units into the two-dimensional space, cluster methods will be applied to divide the units into different groups. For example, in the early years, the hierarchical clustering or K-means clustering method was always combined with multidimensional scaling (MDS) to map and cluster the knowledge unit (White and McCain, 1998; Young et al., 1978). This was followed by the network layout, e.g. Kamada-Kawai (Kamada and Kawai, 1989), Force Atlas2 (Jacomy et al., 2014), Fruchterman Reingold (Fruchterman and Reingold, 1991) and clustering (Modularity based clustering) methods (Newman, 2006). Later, (Waltman et al., 2010) have developed a more advanced and convenient method, called VOS mapping and VOS clustering methods,

Table 5
Some of well know co-occurrence matrix normalization methods in scientometric mapping (Eck and Waltman, 2009).

No.	Matrix normalization methods	Formula
1	Association Strength	$S(c_{ij}, s_i, s_j) = \frac{c_{ij}}{s_i s_j}$
2	Fractionalization	$S(c_{ij}, s_i, s_j) = \frac{1}{2}\left(\frac{c_{ij}}{c_i} + \frac{c_{ij}}{c_j}\right)$
3	Cosine/Ochiai	$S(c_{ij}, s_i, s_j) = \frac{c_{ij}}{\sqrt{s_i s_j}}$
4	Jaccard	$S(c_{ij}, s_i, s_j) = \frac{c_{ij}}{s_i + s_{j-c_{ij}}}$
5	Dice	$S(c_{ij}, s_i, s_j) = \frac{2c_{ij}}{s_i + s_j}$

Note: c_{ij} is number of co-occurrences of item i and j, for example c_{ij} can be number of co-authored papers of author(i) and author(j). s_i or s_j is number of occurrences of an item, for example s_i can be total number of papers published by author(i). $S(c_{ij}, s_i, s_j)$ is the normalized value of i and j.

which is a unified approach which can easily map and cluster scientometric networks. More details about mapping and clustering methods included in each tool, are given in Table 5.

There are several methods to visualize scientometric maps. Table 7 lists some typical visualization approaches: distance-based, graph-based, timeline based, overlay based, and other types. For example, BibExcel has no functions to visualize the results, and the intermediate results can be visualized by Pajek(graph-based) or SPSS MDS method (distance-based). VOSviewer is good at visualizing distance-based and overlay-based networks, especially large-scale networks (see the example in Fig. 5), and the VOSviewer results also can be visualized in a graph-based way by using Gephi or Pajek (see in Fig. 6). CiteSpace is good at visualizing scientometric networks using graph-based maps (see the example in Fig. 7 for document co-citation analysis of 60 papers from Hale Andrew), timeline-based maps, and overlay-based maps (network overlay and journals dual map overlay). As indicated in Section 3, HistCite, CitNetExplorer and CRExplorer can be applied to create timeline-based maps, which is useful to show the evolution of a scientific domain. The example in Fig. 8 shows the timeline-based direct citation links between Hale's 60 papers from Safety Science.

4. Scientometric mapping framework: A brief tutorial

There are many steps in performing scientometric mapping research for a specific topic or subdomain of science. As (Cobo et al., 2011) summarized, the general workflow of scientometrics mapping research includes data retrieval, pre-processing, network extraction, normalization, mapping, analysis, visualization, finally interpretation by an analyst to obtain some (hopefully valuable) conclusions from the results. In order to give a more detailed tutorial-style description of the process of scientometric mapping research, a generic framework is summarized in Fig. 9. The main steps are numbered in the circles in the right-hand part of the figure, and are explained further below.

Step 1. Start scientometric mapping with specific target

Table 6
Methods for data analysis in selected freely available scientometric mapping tools.

No.	Tools	Matrix normalization methods					Mapping methods	Clustering methods
		AS	FTS	Cosine/Ochiai	Jaccard	Dice		
1	Bibexcel	×	×	✓	✓	×	*MDS, Network	Persson's Party Clustering
2	CiteSpace	×	×	✓	✓	✓	Network	Modularity & Louvain algorithm
3	VOSviewer	✓	✓	×	×	×	VOS, Network	CPM & Leiden algorithm
4	SCI2	×	×	×	×	×	Network	EM, Modularity, silhouette & SLM
5	SCIMAT	✓	×	✓	✓	×	Strategic diagram, network	Simple centers algorithm etc.
6	HistCite	×	×	×	×	×	Timeline network	×
7	CitNetExplorer	×	×	×	×	×	Timeline network	Modularity & SLM
8	CRExplorer	×	×	×	×	×	RPYC Curve	Levenshtein similarity

Note: here just list some of widely used methods. AS = Association strength; FTZ = Fractionalization; RPYC = reference publication year spectroscopy. There are many ways to layout the scientometric network, for example Kamada Kawai, Fruchterman Reingold and Force Atlas. SLM = Smart local moving.

Table 7
Survey of visualization approaches in selected freely available scientometric mapping tools.

No.	Tools	Distance based			Graph based			Timeline base	Overlay based	Other types
		VOS	MDS	VxOrd	Kamada-Kawai	Force Directed	Pathfinder			
1	Bibexcel	×	×	×	×	×	×	×	×	×
2	CiteSpace	×	×	×	✓	✓	✓	✓	✓	✓
3	VOSviewer	✓	×	×	×	×	×	×	✓	✓
4	SCI2	×	×	✓	×	✓	✓	✓	✓	✓
5	SCIMAT	×	×	×	×	×	×	✓	×	✓
6	HistCite	×	×	×	×	×	×	✓	×	×
7	CitNetExplorer	×	×	×	×	×	×	✓	×	×
8	CRExplorer	×	×	×	×	×	×	✓	×	×

As indicated in Fig. 9, every research should begin with clearly defined research purposes. Once a given topic or scientific subdomain is defined, research questions about this domain should be formulated. Questions about the scope and focus of the analysis can be developed using the 5W1H methods or Heilmeier Catechism (Shapiro, 1994). For example, what questions you want to answer? Why it is important for the scientific community? Who is your potential reader? After you have a clear research purpose, the actual research questions can be further specified, acknowledging the aims of the available scientometric analysis tools. For instance, questions can relate to author collaboration networks to gain insight in knowledge exchange and social dynamics in a research community, co-citation linkages between highly-cited articles to gain insight in clusters of connected ideas, or historic development trends identified based on term analysis or connections between historically impactful articles. Once the research aims, scope, and focus is clear, and research questions are formulated, the data collection process can be initiated.

Step 2. Data preparation and pre-processing

As shown in Fig. 9, the main actions in this step are the identification of suitable data sources, the definition of search and data retrieval strategies, construction of an initial local dataset, and data pre-processing. These are described next.

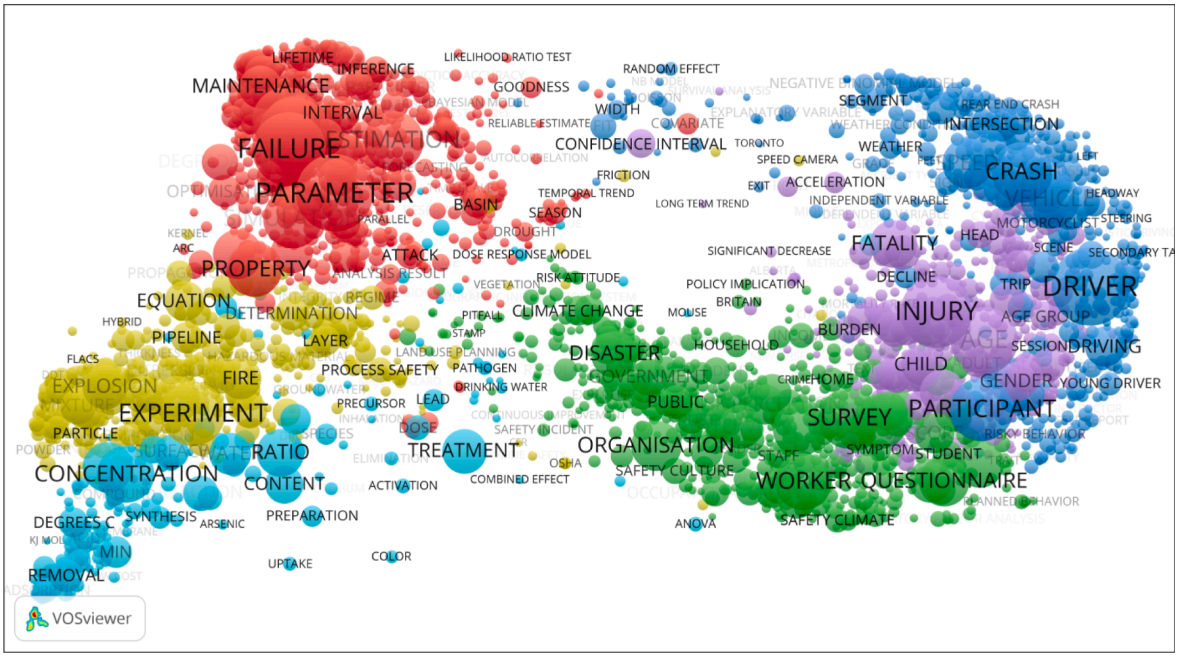
GIGO (Garbage In, Garbage Out) is a well-known concept in e.g. the computer sciences, which means that with flawed or incoherent input data, algorithms processing such data will produce misleading or meaningless outputs. Hence, the quality of the input data for the scientometric analyses one of the key elements for methodologically sound scientometric mapping research. Poor data quality in terms of missing or ambiguous data fields in the database can significantly hamper the accuracy and reliability of the results. Even more serious is a poorly constructed dataset, i.e. without clear, traceable, and well-chosen keywords and criteria for including articles in the dataset for scientometric analysis, the results are very likely to provide little useful insights, or can be seriously misleading.

Even though the present time has been characterised as the big data age, which is reflected in the fact that there is no lack of bibliographic data for scientometric mapping research, there are some important challenges to address in the data collection stage. Collecting high quality data is key, but there is no perfect bibliographic database in the world: each of them has its own advantages and disadvantages, and all databases contain errors and ambiguities. For example, as indicated in Section 3.2, the Web of Science database has a higher quality than other databases. However, the Google Scholar database has a higher coverage than other databases. A researcher should carefully identify which bibliographic database is best suited for the identified research purposes, as e.g. some databases contain poor coverage of certain domains of science. Generally, Web of Science and Scopus are considered to be suitable data sources for scientometric mapping in safety research related topics.

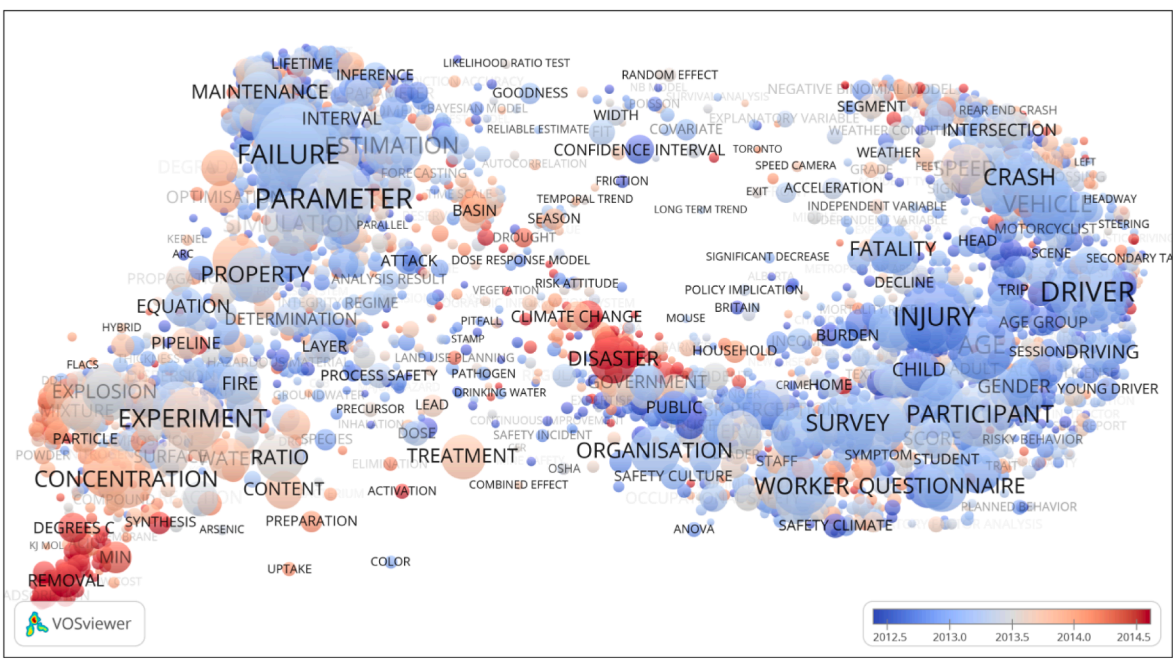
As soon the data source is chosen, it is important to understand the functionalities of the search and data retrieval system, using appropriate keywords and search strategies to construct a comprehensive database which accurately covers the topic or scientific domain of interest. For example, search operators such as 'and' and 'or' are commonly used in the data retrieval process, and filters can be set e.g. to exclude articles from certain journals or topical categories. Such efforts are important to identify and select data with high relevance to the identified analysis scope and focus. Sometimes a balance should be thought between the precision and recall ratio in the data collection. With the data source and data retrieval strategies completed, the data can be downloaded, and the local dataset constructed. In scientometrics, the records downloaded from e.g. Web of Science, constituting the local dataset, are denoted the citing articles. The references found within these citing articles are known as the cited references or cited articles.

Data pre-processing is an important process which can lead to more reliable and accurate results. Some of the data pre-processing should be done before the data analysis stage, whereas some aspects of data pre-processing is better done after an initial analysis of the local dataset. An example of the former is checking whether the data format meets the requirements of the research purposes. Sometimes, it is necessary to normalize (stem, lowercase and tokenize) the text before analysing the terms in the text. An example of the latter, discussed further below, concerns the disambiguation of author names (Liu et al., 2015).

Step 3. Data Analysis



(a) terms clusters of safety science



(b) Terms average publications year of safety science

Fig. 5. Co-words map of safety science (distance-based map, with 23 safety related Journals created by VOSViewer) (Li et al., 2018).

After the data preparation and pre-processing, the initial analysis can be initiated, and an in-depth pre-processing of the data should be undertaken. Typically, many errors and ambiguities in the initial dataset will be found, and such occurrences should be revised based on the analyst's domain knowledge. For example, the name of authors or institutes is sometimes entered in the database in different ways, and the analyst must engage in a disambiguation process to avoid biases and unreliabilities in the results. Depending on the aims of the analysis, also keywords or terms may need to be harmonized, e.g. where abbreviations are used. For instance, "SMS" denotes the same concept as "Safety Management System" and should only be included once in a term analysis mapping.

There are many knowledge units which can be chosen as a focus of the research question, including authors, keywords, documents, and references. For example, authors information can be extracted to identify the highly productive authors and to determine collaboration linkages between authors. After a knowledge unit is chosen from the data (for example, author), the co-occurrence matrix of this knowledge unit can be obtained. In the cells of a co-occurrence matrix, the numbers denote the number of papers co-authored between the authors in the rows and columns of the matrix. There are several normalization methods which could be used to normalize the co-occurrence matrix in

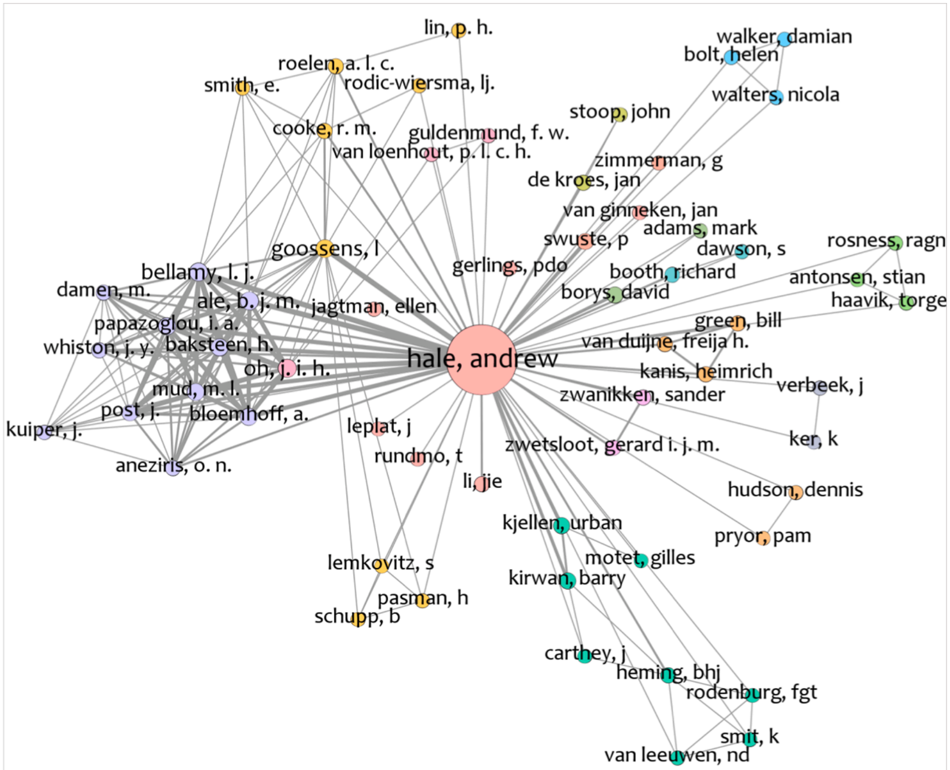


Fig. 6. Hale's co-author network of the publications in Safety Science Journal layout with Force Atlas2 (Graph based map, 60 papers of hale from Safety Science journal (1999–2019) was download and analysed. Including 61 authors and 184 collaboration links). In order to present the example of the different visualization methods, we have downloaded 60 publications from Web of Science, published by Hale Andrew in Safety Science from 1991 to 2019.

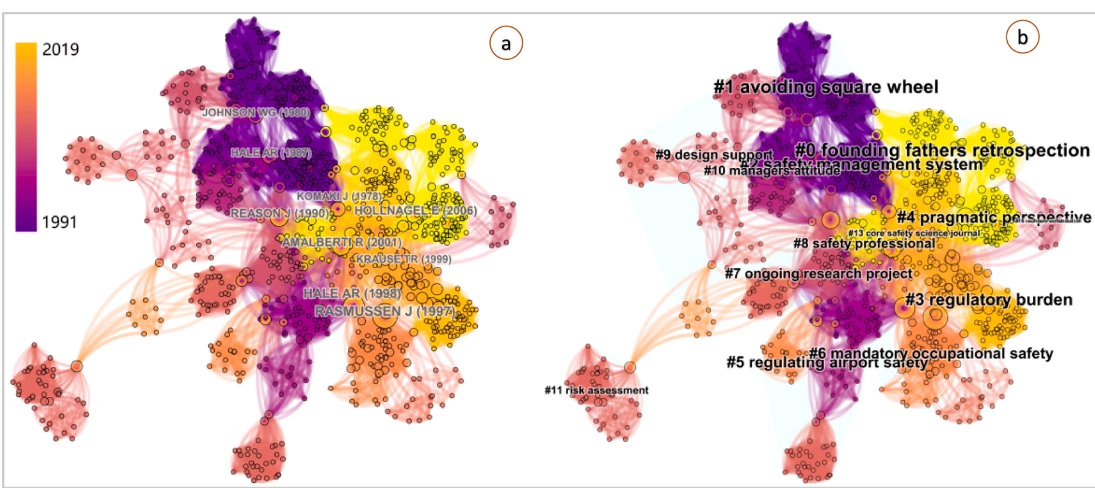


Fig. 7. Graph based visualization of document co-citation network of 1092 references cited by Hale's 60 papers based on CiteSpace (a. document co-citation network, b. clusters of document co-citation network).

scientometric mapping research, for example Salton's cosine, Jaccard's index and association strength, with the default settings of the scientometric mapping tools usually giving reasonable results. It is nevertheless recommended to try alternative normalization methods and (if applicable) parameter settings, as this may lead to easier interpretation of the visualized results.

Step 4. Interpretation and conclusion

The interpretation and the conclusion of the scientometrics mapping results should be based on the obtained visualizations, and usually require familiarity with the topic or scientific domain under investigation. Thus, it does not suffice to be familiar with scientometric mapping methods and tools, but a certain level of familiarity with the research topics will be necessary to gain more meaningful insights and conclusions. Put otherwise, knowledge of scientometric methods and skills with using scientometric mapping tools are necessary to obtain reliable and clear results. Good knowledge and experience with the domain of research will be of great value in interpreting the collaboration and co-citation networks, historic development trends, and term maps, facilitating the writing of a meaningful narrative about the visual results. Hence, it is recommended that researchers who are less familiar with a research topic or scientific domain, also engage in more content-focused literature review types, such as an overview / narrative review, or a

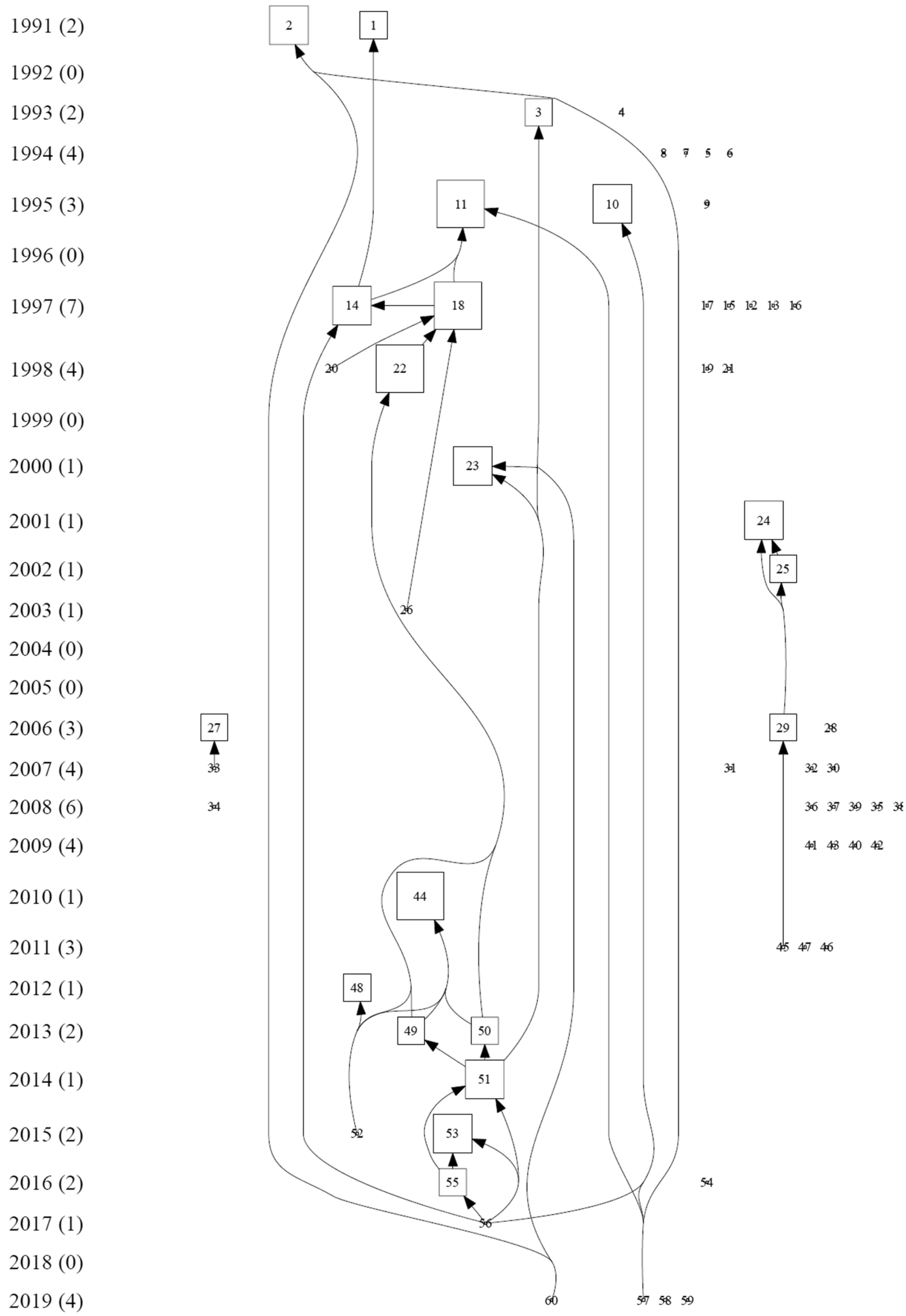


Fig. 8. Timeline based map of Hale's 60 papers with 60 nodes and 35 links (the number inside the box is a paper, and detailed information of the papers is provided in appendix 1.)

more comprehensive state-of-the-art review, see (Grant and Booth, 2009).

Scientometric mapping research is primarily intended to give a wide view of a research domain, as its methods, relying on statistical analyses, work best with relatively large datasets. This leads to a methodological contradiction in the sense that larger datasets are better for constructing scientometric maps, whereas larger datasets mean that it may be practically impossible to review the actual literature in some level of detail. Hence this means that it may be hard to interpret the results as a single researcher. Therefore, it is suggested that as an alternative or an addition to reviewing the actual literature, an online survey or selected interviews with domain experts are performed, to interpret the results.

5. Discussion

Scientometric mapping analysis has become popular in the scientific communities. Originating from information and library sciences, its methods have spread to computer science, business economics, engineering, and other research domains. As a relatively recently applied method in the safety science domain, some best practices should be adhered to, to ensure accurate, reliable, and insightful results are obtained and reported in the literature.

Firstly, as indicated also in Section 2, some papers utilizing scientometric mapping approaches do not include any data cleaning process. This means that the resulting analyses, such as the number of co-

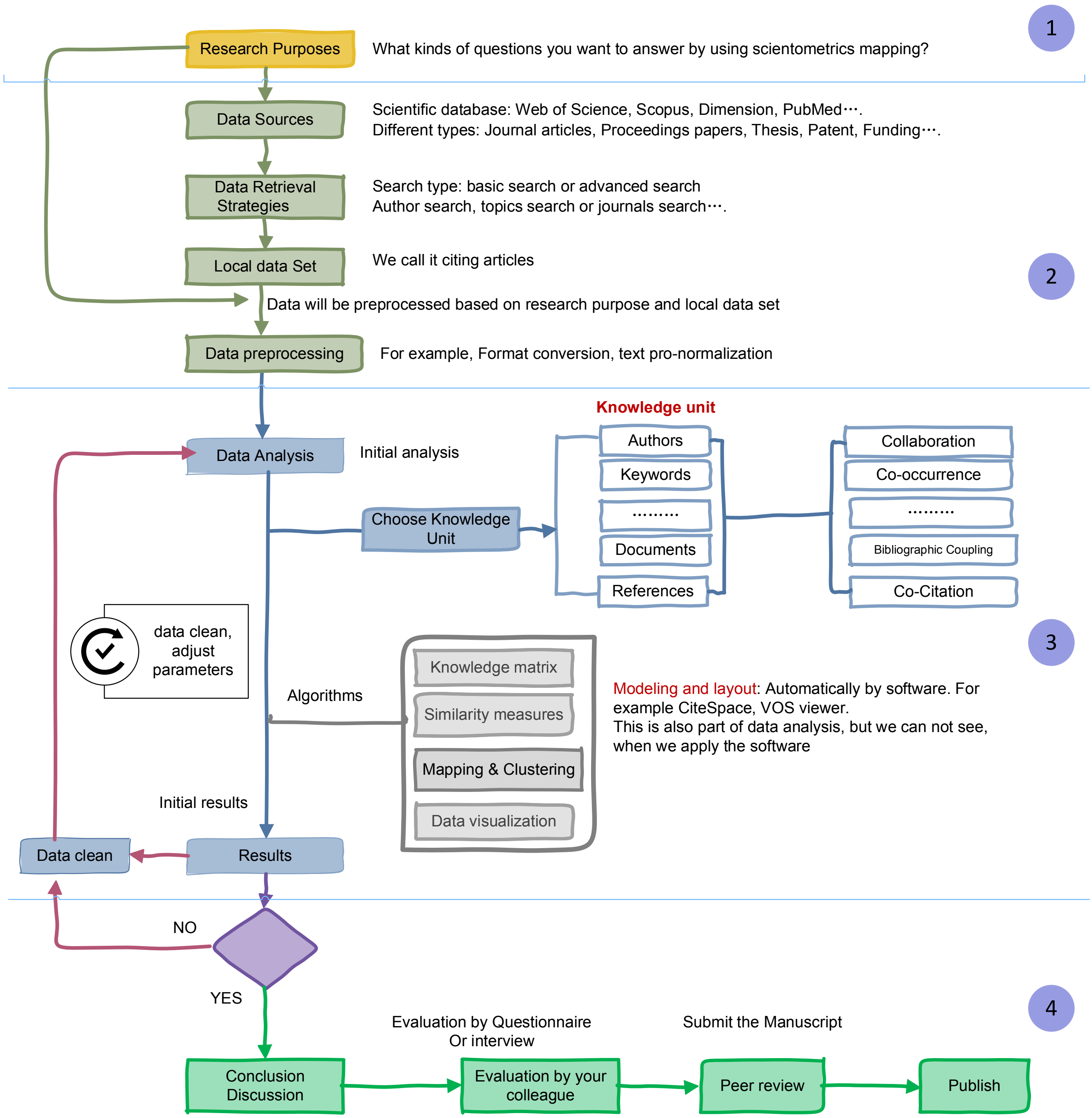


Fig. 9. Framework of scientometric mapping research: an overview of the steps.

authored papers or term occurrences and linkages, may very well be unreliable and biased, leading to poor or erroneous results. As outlined in Section 4, application of a (possibly iterative) data cleaning process should be is a prerequisite for accepting scientometrics articles in academic journals.

Secondly, every method has limitations, and so do scientometric mapping approaches. Even though scientometric mapping tools are useful to help researchers and other stakeholders understand the scientific work on a given topic or domain (such as safety science), limitations of the scientometric mapping techniques and the obtained results should be acknowledged, expressing uncertainties (e.g. about data coverage) as needed. As a data-driven approach, scientometric mapping is an empirical and objective way to analyze knowledge domains. However, for the interpretation of the mapping results, it is indispensable to use expert knowledge, either of the researcher(s) executing the analyses, or for other domain experts. Limitations of domain knowledge and possible subjective biases in interpreting the results, should be acknowledged. One way to limit the importance of these shortcomings, is to validate the findings by having the results and interpretations checked by an independent domain expert. It is furthermore essential that the data-driven approach starts with meaningful research questions, which have a clear contribution to the understanding and development of the domain. The relevance to safety practitioners and safety researchers, e.g. through highlighting structural disagreements within the field, or by specifying future research directions, should be made very concrete. For editors and reviewers, it is recommended to avoid accepting purely descriptive articles, which have no meaningful research objective, interpretations or implications.

Thirdly, science maps should have a clear structure, and be easy to understand for the readers. It means the underlying algorithms and parameters in the tools also need to be understood and applied to improve the results. On the other hand, the interpretation is also important for certain aspects in scientometric mapping analysis. In order to tell a good 'story' of your map, you must have much more knowledge in your topics. You could find a suitable collaborator, or you may do an online survey or interview from your domain experts.

6. Conclusions

In this article, an overview has been given of the safety-related research topics and domains to which scientometric analysis and mapping methods have to date been applied. This overview is used to identify a number of methodological shortcomings in some of this literature. It also shows that only a limited range of tools and analysis types has been used to address safety research sub-domains, if compared to the suite of freely available scientometric mapping tools.

Based on this, an overview of some key concepts, methods, and tools of the scientometric mapping research domain is given. Rather than addressing technical details of the methods, for which the specialized literature is referred to, focus has been on what kinds of research questions this kind of methods are best suited to answer. Key concepts such as direct citation analysis, bibliographic coupling, co-citation analysis, co-word analysis, and co-authorship analysis are introduced. Data sources are outlined and tools for performing scientometric analyses described, focusing on which research questions these are well-suited to provide an answer.

Subsequently, a brief tutorial is presented, where a typical scientometric mapping framework is described, consisting of four main steps. First, a specific research domain is defined and target research questions are formulated. Subsequently, a suitable data source is selected, and data is obtained through a well-considered search strategy. This data is further processed so that an accurate and comprehensive dataset is finally retrieved from the selected article database. Third, the data is analyzed. Here, a pre-analysis is performed to disambiguate errors and duplicate knowledge units in the dataset. Then, using a selected scientometric mapping tool, the research question is addressed by applying the functionalities of the tool to the dataset. As a last step, the results obtained from the quantitative analysis and mapping visualization are interpreted. Here, in order to obtain meaningful insights, it is important that this interpretation is performed by a researcher who is knowledgeable about the selected research domain. This can be achieved by performing other types of literature reviews to the articles in the dataset alongside the scientometric mapping work. Alternatively, the analysis results can be inspected by with domain experts, e.g. using interview or survey techniques, so that a researcher can develop an insightful narrative about the research domain, in light of the defined research questions.

This article can support the development of scientometric research within the safety science community, so that a wider range of tools can be applied to answer more diverse research questions about safety science subdomains. Finally, the tutorial and discussion on best practices can ensure that high-quality results can be obtained and reported, and it can support reviewers and editors in making sound judgments about submissions where scientometric techniques are applied.

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Appendix A. Supplementary data

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