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A systematic review of safety risk assessment research in China

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ABSTRACT

The rapid industrialization and urbanization in China require a high level of safety management and thus urge the development of safety risk assessment in China. In the past two decades, many safety risk assessment research findings have been published in international journals by Chinese scholars, while it is not clear the development progress and China's contributions to the world in this research field. Therefore, a systematic and thorough literature review is conducted to investigate risk assessment research in China. Firstly, the research publications authored by Chinese scholars are searched from the well-known literature database Web of Science to support the analysis of risk assessment research in China. Secondly, a bibliometric analysis is conducted for the obtained literature related to risk assessment research in China to find out publication trends, research organizations, research authors, research topics, and research methods. Then, a thorough analysis of research topics and research methods is carried out to present the research progress. Finally, possible future research issues in the risk assessment research domain are discussed based on this literature review. According to the discussion, more attention in China should be paid to the risk of digital or autonomous systems, the risk related to extreme events, and the risk in large cities.

1. Introduction

In the safety domain, risk is always referred to as the consequences and uncertainties of events, and the uncertainties are usually represented by probabilities [1,2]. Safety may be defined as the antonym of risk and safety can refer to an acceptable risk [3]. As a result, a risk assessment is a description of risk to find out what can occur, how likely it will occur, and what the consequences are if it occurs [4]. To conduct a risk assessment, the essential task is to address the uncertainties in physical models and state-of-knowledge uncertainties about the parameters and assumptions of these models [5]. Paté-Cornell [6] divided uncertainties into two categories: aleatory and epistemic uncertainties. The former refers to randomness in samples while the latter represents the situation with a lack of knowledge about fundamental phenomena. Besides, expert knowledge may also be used for risk assessment for tracking rare events and Bayes' theorem can also help update the probabilities given new information and evidence. According to these fundamental studies, risk assessment has progressively emerged as a crucial means of safety assessment and management, with widespread application across diverse sectors, encompassing the chemical industry, nuclear industry, and the construction sector, among others [7–9].

The term "risk assessment" has a history of more than 2000 years while risk assessment was considered a science in the academic domain only from the 1980s [4,10]. Over the past 40 years, risk assessment has obtained rapid development in qualitative risk assessment, quantitative risk assessment [11], dynamic risk assessment [12], rare event assessment [13], etc. Many risk assessment approaches have been developed or applied in the safety domain to better describe safety risks, such as risk matrix [14], Bayesian network [15], event tree [16], fault tree [17], bow-tie [18], and dynamic graph [19]. This progress in safety risk assessment greatly promotes the development of risk-informed safety management and thus improves safety worldwide [2,20–22].

As the world's most populous country, China faces unique challenges in risk assessment due to the sheer scale of its social and economic activities. Consistent with the development stage of risk assessment research, China has started to develop its economy rapidly with industrialization and urbanization in recent decades, being the world's second-largest economy since 2010. To meet the needs of

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industrialization and urbanization, China's central government and local governments have already taken a lot of measures to improve safety in China. Safety science has become an independent discipline in China. Now more than 200 universities have bachelor's education programs and over 20 universities have doctoral education programs in safety science. China established the Ministry of Emergency Management (MEM) to integrate different safety resources for effectively preventing and controlling accidents and disasters [23]. In the academic domain, China has achieved remarkable innovation. China's research endeavors in the realm of safety science have witnessed a remarkable surge, affording profound insights into safety principles and fundamental concepts. Furthermore, the research has culminated in the development of innovative methodologies, tools, and processes for assessing and managing safety effectively. China has been the most productive country in terms of publications in the main international safety-related journals [24–26].

In light of China's contributions to safety science and engineering, some attempts have been made to investigate safety research in China. Zhao et al. [27] investigated process safety challenges of small and medium-sized enterprises in the chemical sector in China. Zhao et al. [28] studied process safety management in China and demonstrated that improving chemical process safety management and emergency preparedness can promote sustainable development in the chemical industry. Wang et al. [29] analyzed the work safety plan in China from 2016 to 2020, including the current status, new challenges, and future tasks. Yang et al. [25] reviewed China's process safety research by a bibliometric analysis to find out the research progress. Chen and Reniers [23] analyzed the current status, safety problems, and pathways for future chemical safety research in China. Li et al. [24] investigated the international process safety research in China and analyzed the collaborations, research trends, and intellectual basis. Ge et al. [30] reviewed the causation models of accidents developed from 1978 to 2018 in China and thoroughly analyzed five accident causation models.

However, scarce attention has been paid to risk assessment research in China, and the contributions of Chinese scholars to the development of safety risk assessment are unclear. Given the influence and special contributions of China in safety science and engineering indicated above, systematic bibliometrics research on risk assessment in China is beneficial to the sustainable development of safety science in China and even the world. As a result, this study conducted a systematic study on risk assessment research in China, to find out the development progress, status, and future needs.

2. Methodology

A systematic literature review methodology with four steps is developed to analyze risk assessment research in China in the past decades, as shown in Fig. 1.

The first step is to search and refine literature based on the WOS database. A literature search is conducted based on the Web of Science (WOS) Core Collection, an international literature database owned by Clarivate. WOS originated from the Science Citation Index (SCI) which is well-known in China's academia. In the 1980s, China started using SCI papers to evaluate the academic levels of researchers and institutions, and then most important academic outcomes were published in the journals indexed by WOS. Besides, most of the journals indexed by WOS publish papers in English, making the research outcomes more accessible to readers around the world. Therefore, selecting WOS as the literature database can reflect the main contributions and influence of China on risk assessment research. Internationally renowned academic journals usually have a wide readership and influence, and the papers in these journals are often quickly paid attention to by researchers around the world, thus promoting the wide dissemination and application of scientific research results. In addition, English is the main language of international academic exchange, and publishing papers in English promotes communication and cooperation with international counterparts. This not only promotes China's scientific research to be in line with international standards, but also provides more cooperation opportunities and resources for Chinese researchers and promotes the rapid development of China's scientific research. Given the above reasons, important Chinese scientific research results and high-level papers choose to prioritize publication in English in internationally renowned academic journals to meet the data source requirements of the bibliometric analysis in this paper. Therefore, published Chinese publications are not considered in this paper. The search is set as follows: Title: risk assessment OR risk analysis OR risk evaluation; Address: China; Not Topic: health, environment, and food. The research scope of this study focuses on safety science and engineering in China. Safety science and engineering is a comprehensive Chinese national-level discipline, covering three levels: safety science, safety engineering, and the intersection between the two levels. Research and applications are mainly focused on industrial safety, system safety, and other areas. Therefore, irrelevant search topics of non-engineering are excluded: health, environment, and food, to improve the efficiency of subsequent data cleaning. Based on the search results, refining work is needed to exclude the literature that is not related to risk assessment in China.

In the second step, a bibliometric analysis based on VOSviewer is used to assist in scholar analysis, research organization analysis, research methods analysis, and citation analysis [31,32]. VOSviewer is a bibliometric analysis software, widely used in the academic domain to review a research topic [33–36]. VOSviewer can generate different kinds of maps based on bibliometric data for visualizing and exploring many literature documents [37,38]. In this study, we mainly use the text mining function to find out research topics and methods. The text mining function offered by VOSviewer is used to construct and visualize co-occurrence networks of important terms extracted from keywords and abstracts of scientific literature. In that case, the research topics and methods used in different stages can be analyzed to show the development trends and evolution of risk assessment research in China.

The third step is to thoroughly analyze the research topics and methods. According to the obtained research topics and research methods obtained from the bibliometric analysis, a thorough analysis of research topics and methods is conducted to present Chinese scholars' contributions in the safety risk assessment domain and get insight into the current status of the research in China. The analysis is based on research publications obtained from the Web of Science and the most cited publications are always used for analysis. Besides, selected papers are analyzed according to the publishing time to show the development and evolution process of research topics and methods. This step is the core of the developed methodology and a basis for the discussion of future risk assessment research needs in China.

The last step discusses the pathways for future safety risk assessment research in China. In this step, the contributions of China to risk assessment research are summarized according to the discussion results in Steps 2 and 3. The limitations of safety risk assessment research in China are analyzed by comparing the research outcomes with the research around the world. Finally, some recommendations on pathways for future risk assessment research in China are discussed to promote the development of risk assessment research and practices in

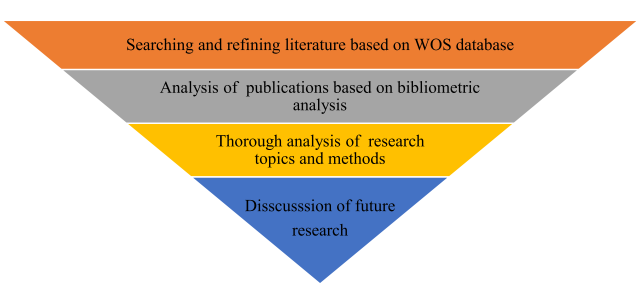

Fig. 1. A systematic literature review methodology with four steps.

China, thus making China safer.

3. Results

In this section, we analyze the research publications, research organizations, research authors, research topics, and research methods related to safety risk assessment in China.

3.1. Research publications

According to the first step of the developed methodology, the search work is conducted on 23, May 2022, and 2062 papers are obtained from the WOS database. By reading the titles and abstracts of these papers, these papers are refined to exclude papers that are not related to safety risk assessment in China. Finally, a total of 1449 papers related to safety risk assessment in China are obtained and the following analysis work is based on the refined papers. In the WOS database, the first paper focusing on safety risk assessment in China was published in 1993 [39], while the number of papers only started increasing after 2005, as shown in Fig. 2. The number of publications each year shows an increasing trend after 2005. The number of publications in 2021 is 26 times greater than that in 2005. It demonstrates that safety risk assessment has obtained rapid development over the past two decades.

3.2. Research organizations

A total of 1102 authors are identified from the obtained 1449 papers. Of these organizations, 102 organizations have at least 5 publications, as shown in Fig. 2. The top 10 most productive organizations are listed in Table 1. As shown in Fig. 3, the color represents different cooperative clusters. For instance, the blue cluster represents risk assessment research related to transportation safety. This cluster consists of many famous universities in the transportation domain such as Wuhan University of Technology, Beijing Jiaotong University, Tongji University, and Southeast University. The red cluster represents the research related to risk assessment of hazardous materials, led by the China University of Petroleum (Huadong campus and Beijing campus). Delft University of Technology (TUD) from the Netherlands is also included in this cluster since there are many cooperations between TUD and China and the cooperation domains mainly contain hazardous material risks and transportation risks.

Table 1 shows the top 10 most productive organizations. The most productive organization in China is the China University of Petroleum focusing on hazardous material risks, followed by the Wuhan University of Technology focusing on transportation risks, and the China University of Mining and Technology (Xuzhou campus and Beijing campus) focusing on mining risks. It demonstrates that people in China pay the most attention to three domains: hazardous material risks, transportation risks, and mining risks.

Table 1
Top 10 productive organizations in China.

No.	Organization	Documents	Citations	Total link strength
1	China University of Petroleum	76	1046	23
2	Wuhan University of Technology	68	828	38
3	China University of Mining and Technology	53	387	15
4	Beijing Jiaotong University	53	275	13
5	Tsinghua University	52	475	28
6	Tongji University	50	980	24
7	Hohai University	28	161	7
8	Tianjin University	27	215	11
9	Chinese Academy of Sciences	26	448	12
10	Shanghai Maritime University	26	301	9

3.3. Research authors

A total of 4648 authors are identified from the obtained 1449 publications while only 15 authors have at least 7 publications related to safety risk assessment, as shown in Table 2. This result indicates that only a few Chinese scholars mainly focus on research related to safety risk assessment. The most productive author is Guoming Chen, followed by Xinping Yan, Di Zhang, and Laibin Zhang. The most cited author is Xingping Yan, followed by Guoming Chen, Wei Wang, and Di Zhang.

Fig. 4 shows the cooperative clusters between different authors. Two members of the Chinese Academy of Engineering are shown in this figure: Laibin Zhang and Xinping Yan. Laibin Zhang leads the cooperative cluster focusing on oil and gas safety at China University of Petroleum (Beijing) while the researchers around Xinping Yan mainly focus on maritime risks and are mainly from Wuhan University of Technology. Besides, Juncheng Jiang leads the group at Nanjing Tech University, focusing on chemical and process safety risks. Guoming Chen leads the research group at China University of Petroleum (Huadong) and he has many international cooperations with Faisal Khan, a professor from Memorial University of Newfoundland (Texas A&M University). Besides, Genserik Reniers from TUD has much international research cooperation with Guohua Chen from the South China University of Technology.

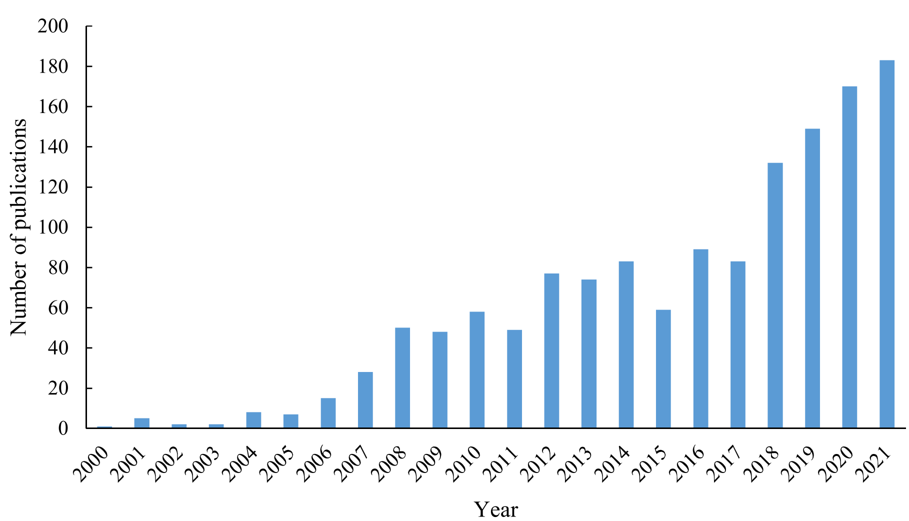

Fig. 2. The number of publications related to risk assessment in China published each year.

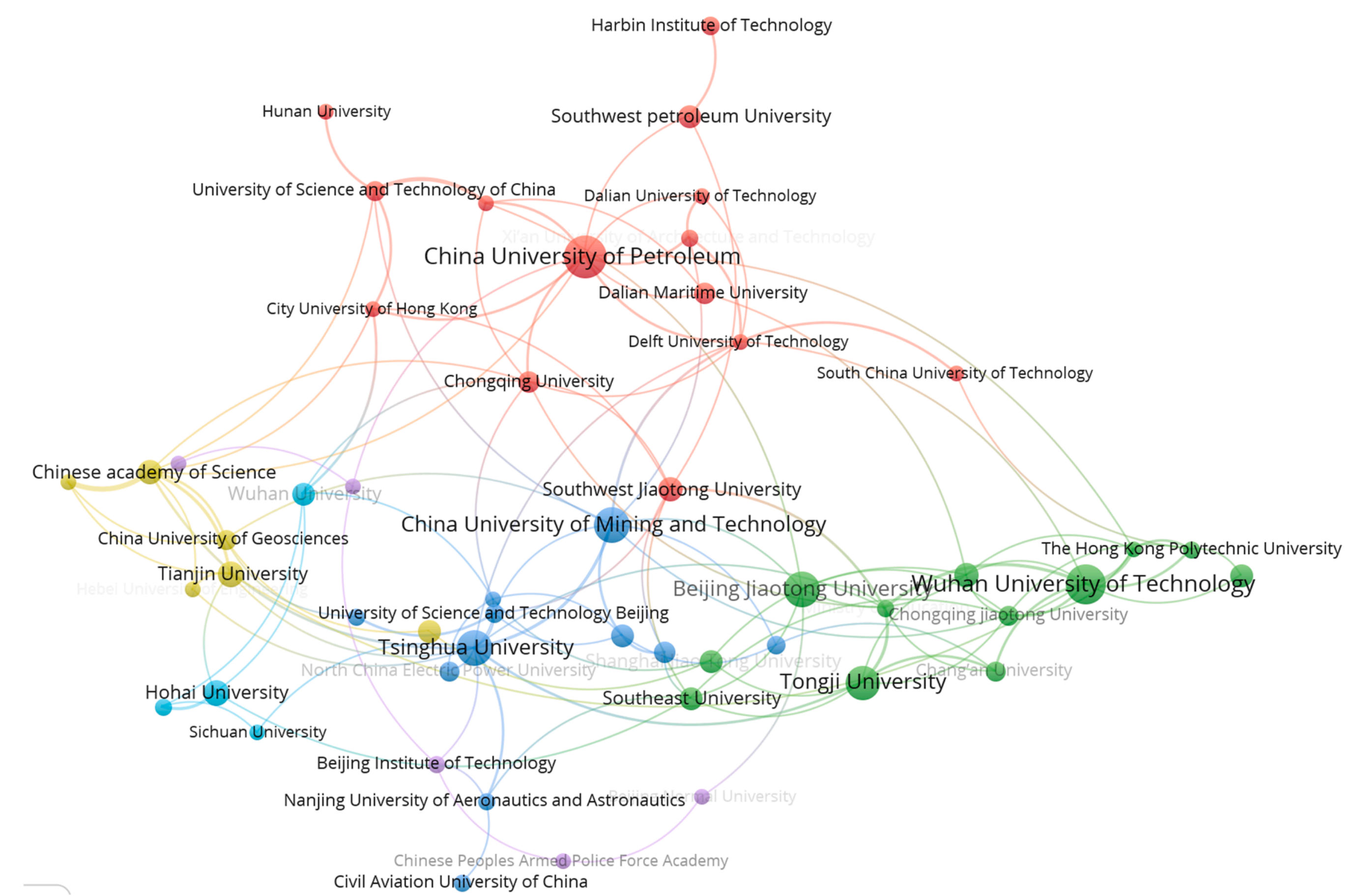

Fig. 3. Cooperation networks between different organizations.

Table 2
Authors that have at least 7 publications on safety risk assessment in China.

No.	Authors	Documents	Citations	Total link strength	Research topic
1	Chen, Guoming	15	341	13	Hazardous material risk
2	Yan, Xinping	10	365	14	Maritime risk
3	Zhang, Di	10	254	12	Maritime risk
4	Zhang, Laibin	9	210	4	Hazardous material risk
5	Wang, Wei	9	316	1	Road traffic risk
6	Wang, Yang	9	22	0	Structure risk
7	Li, Xinhong	9	230	9	Hazardous material risk
8	Zhang, Jinfen	8	221	9	Maritime risk
9	Cai, Baoping	7	132	1	Hazardous material risk
10	Guan, Zhichuan	7	25	4	Hazardous material risk
11	Hu, Jinqiu	7	51	4	Hazardous material risk
12	Wang, Hao	7	135	1	Mining risk
13	Wu, Jiansong	7	62	2	Hazardous material risk
14	Yang, Zaili	7	236	7	Maritime risk
15	Zhang, Bo	7	31	4	Hazardous material risk

3.4. *Research topics*

By analyzing the keywords of the 1449 papers, we find that most of the papers focus on traffic risk, followed by hazardous material risk, structure risk, construction risk, mining risk, energy system risk, and urban risk.

3.4.1. *Traffic risk*

Traffic risk involves maritime risk, railway risk, air traffic risk, road traffic risk, and public traffic risk. Researchers in the maritime domain in China mainly focus on collision, grounding, flooding, overboard, etc. Among these topics, collision risk obtains the most attention since collision is the most common accident in maritime transport [40,41]. In recent years, more attention has been paid to multi-vessel collision risk, maritime traffic risk near offshore wind farms, and the risk of autonomous ships. Besides, many scholars pay attention to the risk of railway and train systems, including traction power-supply system risk, train control system risk, train door system risk, maglev train system risk, collision risk, and hazardous material transportation risk. With the rapid development of high-speed trains and some severe accidents of high-speed trains such as the Wenzhou high-speed train collision accident in 2011 [42], an increasing number of scholars have conducted research on the risk of high-speed train systems.

3.4.2. *Hazardous material risk*

Many researchers in China conduct risk assessments related to hazardous materials such as transportation pipeline risk, chemical plant risk, drilling and blowout risk, hydrogen risk, etc. Pipeline risk assessment covers urban gas pipelines, gas pipelines in underground utility tunnels, subsea pipelines, supercritical CO_2 pipelines, etc. Accident

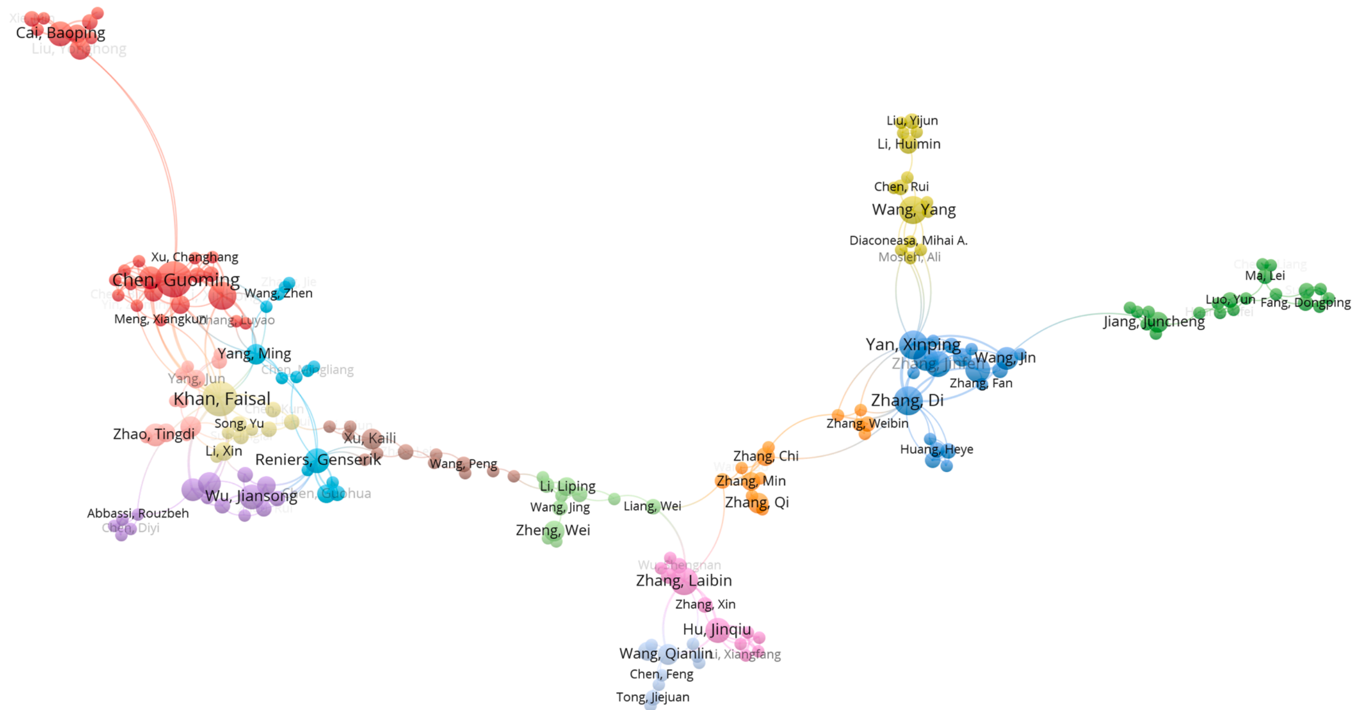

Fig. 4. Cooperation networks between different authors.

scenarios considered in risk assessment include failure, leakage, fire, explosion, and hydrate blockage. Chemical process risk mainly includes chemical process risk and major risks (fire, explosion, leakage). Since many hazardous materials are stored, processed, and transported in chemical plants, domino effects [19] are always considered in chemical plant risk assessment [43]. In oil and gas exploitation, the consequences of blowout are the most severe. For instance, The deepwater horizon blowout accident resulted in 11 fatalities and 17 injuries in 2011 [44]. Accidents caused by offshore oil and gas exploitation not only can result in casualties, but also may lead to sea pollution and ecological disasters. Therefore, deepwater and offshore drilling risks have been thoroughly studied in recent years [45]. With the wide application of hydrogen energy, the risk caused by hydrogen has obtained increasing attention in China [46].

3.4.3. *Structure and construction risk*

Structure and construction risks mainly include tunnel risk, dam risk, subway risk, and building risk. In the tunnel safety domain, schools in China consider structural safety risk (e.g., water inrush), construction risk, and hazardous material release risk (LNG transportation, natural gas pipeline). The types of tunnels include highway tunnels, metro tunnels, subsea tunnels, urban underground utility tunnels, etc. Dam risk includes overtopping risk, dam break risk, seismic risk, landslide risk, the environmental risk caused by dam break, cracking risk, etc. In addition to dams and subways, China now has more than 7000 km of subways, thus subway risk also obtains increasing attention, including subway stampede risk, equipment risk such as escalators, metro construction risk, fire risk in subway stations, and emergency evacuation risk, etc. In terms of building risk, China's scholars mainly focus on building fire risk in light of many high-rise buildings in large cities [47].

3.4.4. *Mining risk*

Mining risk in China always refers to coal mining risk since coal is the main primary energy source in China [48]. A methane explosion may lead to many fatalities in a coal mine, thus many researchers in China have conducted risk assessments of methane explosions [49]. Critical factors that influence methane explosions such as ignition sources (e.g., electrical spark, blasting, and friction spark), blasting operation, digging process, an explosive charge, and gas detection procedure have been identified in past research. Considering the increase in deep mining, the water-inrush risk of deep mining cannot be ignored in China [50]. Besides deep mining, mining undersea also needs to deal with seawater inrush risk since most of the mines may be under the sea [51]. The depth of underground mines also leads to the risk of coal–rock dynamic disasters such as rockburst and coal bursts. As a result, Chinese scholars have also developed risk assessment methods for estimating risk to ensure mining safety [52].

3.4.5. *Energy system risk*

Risk assessment research in China mainly considers electric power grid risk and nuclear power risk. Electric power grids play an essential role in the operation of electrically driven systems [53], past research considered the risk of traction power-supply systems, metropolitan power grids, power transmission channels, wind power integrated power systems, etc. In terms of nuclear power risk, scholars in China always pay attention to the risk of nuclear power plants since radionuclides may be released from a nuclear power plant accident [54]. Besides, some researchers also pay attention to the fuel supply chain of nuclear power plants to ensure the safety and security of radioactive fuel transport [55].

3.4.6. *Urban risk*

Rapid urbanization in recent decades has produced many large cities in China, so the urban risk has obtained increasing attention. Due to the complex compositions and functions of cities, many risks exist in cities such as waterlogging/flood disaster risks [56], urban transport risks (e.g., urban rail transit, crash risk) [57], hazardous material risks (e.g., natural gas pipelines, underground utility tunnels) in urban areas [58], fire risks [59], etc. Among these risks in urban areas, waterlogging/flood disaster risks, the risk related to hazardous materials, and transport risks in urban obtain the most attention given the number of publications.

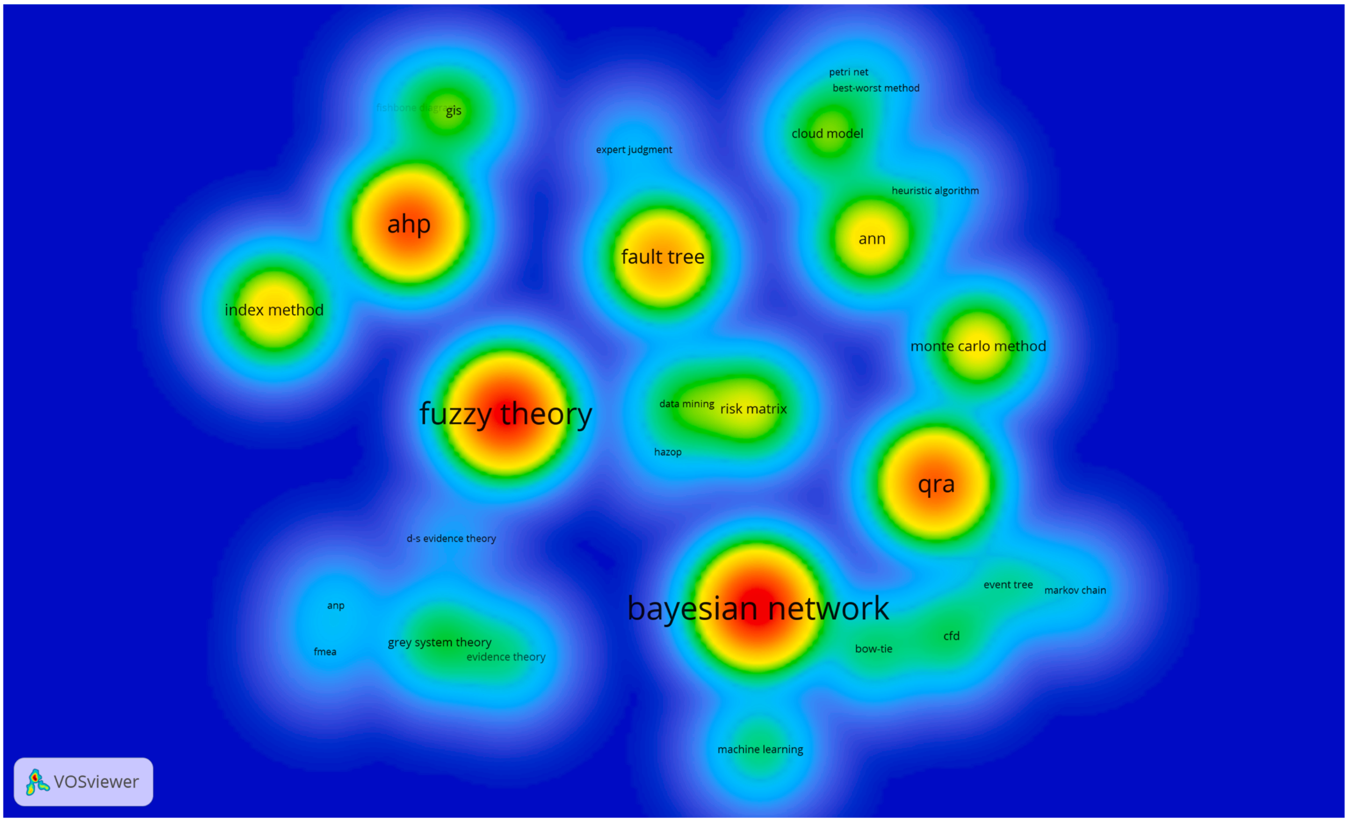

Fig. 5. Research methods of safety risk assessment in China.

3.5. Research methods

According to the keywords set by the authors, we can identify the main risk assessment methods used by scholars in China. As shown in Fig. 5, 32 methods are identified and the frequency of each method is represented by the size of the words and the color. The frequency increases with increasing word size. The most frequent method is Bayesian networks, followed by fuzzy theory, Analytic Hierarchy Process (AHP), quantitative risk analysis (QRA), fault tree, index method, artificial neural network (ANN), Monte Carlo method, risk matrix, and cloud model. Table 3 lists the top 10 frequent research methods and their characteristics.

Table 3
A list of the main research methods.

Research methods	Frequency	Characteristics
Bayesian network	94	Model event dependencies, probabilistic inference, probability update
Fuzzy theory	86	Treat uncertainties using ambiguity and vagueness
Analytic Hierarchy Process	66	Make complex decisions based on mathematics and psychology
Quantitative risk analysis	59	present numerical values of the risks
Fault tree	41	Understand the logical evolution of accidents
Index method	26	Comprehensively represent accident frequency and consequence
Artificial neural network	24	Develop complex nonlinear functional relations between risk and risk-influencing factors using data
Monte Carlo method	22	generate random sampling to obtain numerical results, avoiding the complexity of the analytic method
Risk matrix	18	Assist decision making, simple, visibility of risks
Cloud model	14	convert a qualitative concept into a quantitative representation

As shown in Fig. 2, the Bayesian network has rapidly developed in recent years, while index method, fuzzy theory, AHP, fault tree, and event tree are traditional methods. Besides, newly developed methods such as cloud model, machine learning, and best-worse methods also receive increasing attention in China.

3.5.1. Bayesian network

Bayesian network (BN) is a directed acyclic graph based on Bayes' theorem for probability reasoning in which nodes represent variables and directed arcs connect nodes with a dependency relation [15,60]. Bayesian networks work in risk assessment mainly based on probability theory and graph theory by constructing a directed acyclic graph to represent risk events and causal relationships between them, and using Bayes' theorem to calculate the probability of risk events [61]. Bayesian networks are widely used in risk assessment in multiple fields, and the advantage is mainly in the fact that the viewability allows visual representation of the results. Plus, the network model is easy to deal with missing data due to the dependency between the variables of each node of the network. Tang et al. [62] used the Bayesian network for risk analysis of emergent water pollution accidents, considering the human factor of emergent accidents. Zhang et al. [63] developed dynamic Bayesian networks (DBNs) for accident scenario analysis and dynamic quantitative risk assessment for managed pressure drilling, considering the influence of uncertain factors, and the effects of degradation. Chang et al. [64] applied dynamic Bayesian networks for assessing subsea wellhead fatigue failure risk to predict the failure risk under dynamic conditions. Wang et al. [65] developed a dynamic Bayesian network model for analyzing the dynamic risk of deepwater drilling, considering the uncertainty of logical relationships. With the development of dynamic risk assessments, DBN obtained increasing applications in safety risk assessment in China. Bayesian networks suffer from computational complexity and data dependency constraints in practical applications, affecting the efficiency and accuracy of result inference. With the increase in data volume and data diversity, future research will focus on more complex models, such as deep Bayesian networks and high-dimensional Bayesian networks.

3.5.2. Fuzzy theory

Fuzzy logic is an extension of Boolean logic to compute based on "degrees of truth" (0 to 1) rather than the usual "true or false" (1 or 0) Boolean logic and it is widely used for dealing with uncertainties and ambiguities [66]. Fuzzy theory works in risk assessment by introducing fuzzy sets and fuzzy logic to deal with uncertainty and ambiguity. Risk assessment methods based on fuzzy theory can be used to describe the various possible states of risk by establishing fuzzy sets and analyzing the correlations and changes between these states using fuzzy logic and fuzzy relationships. In addition, by qualitatively and quantitatively analyzing the fuzzy sets of risks, it is possible to assess the probability of occurrence of the risk and the degree of loss that may be caused, thus determining the importance and prioritization of the risk. It can be used separately or combined with other risk assessment methods for safety risk assessment. Li et al. [67] established a fuzzy evaluation for estimating collision risk in air traffic management, considering navigation, exposure to risk, and intervention. Wen [68] used fuzzy theory to evaluate the risk of the safety system risk of airlines, considering many fuzzy factors affecting the safety system. Besides, increasing research combines fuzzy theory with other methods to address the uncertainties and ambiguities in risk assessment.

Liu et al. [69] developed a risk assessment method for power grids using AHP and Fuzzy theory in which fuzziness and credibility measures were used to model the uncertainty of the catastrophic effects. Zhang et al. [70] developed a Fuzzy Bayesian Networks (FBN) method by combining Fuzzy logic with BN to model the causal relationships between tunnel-induced damage and its influential variables. Yang et al. [71] used fuzzy comprehensive evaluation and AHP to assess water and sand inrush risk during underground mining. Wu et al. [72] applied Fuzzy logic and risk index to conduct a risk assessment on offshore photovoltaic power generation projects in China. Zhou and Reniers [73] established a fuzzy Petri net approach based on fuzzy logic and Petri net for risk assessment, considering veto factors and non-veto factors. Huang et al. [74] combined fault tree analysis and fuzzy logic for fire risk assessment of battery transportation and storage. Dealing with uncertainty is the most significant advantage of fuzzy theory. In addition, fuzzy theory can simplify complex system models and reduce computational complexity while maintaining high accuracy. However, the formulation of fuzzy rules often relies on the experience of experts, lacking unified standards and theoretical support. Optimizing fuzzy rules and reducing the interference of human factors become the development trend of fuzzy theory.

3.5.3. Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) is a structured approach for organizing and analyzing multi-objective decision-making problems based on mathematics and psychology through qualitative and quantitative analysis [75]. Especially for multi-objective optimization problems, the analytic hierarchy process has its unique advantages, which can determine the weights of each objective and transform multi-objective planning problems into solvable single-objective planning problems. AHP works in risk assessment by breaking down a complex risk assessment problem into multiple constituent factors and constructing a multilevel analytical structural model following the interrelated influences and affiliations among these factors. The degree of influence of each factor on the overall risk is determined quantitatively. Li et al. [76] used AHP to quantify the influence of risk indexes for risk assessment on communication systems with satellite constellations. Yang et al. [77] applied AHP to comprehensively estimate the losses associated with major risks of hydrocarbon storage caverns. Li et al. [78] assessed the oil spill risk of port tank zones using AHP and Fuzzy logic for early discovery of tank zone oil spill accidents. Guo et al. [79] used AHP to obtain the weights and scores of risk indexes for assessing the risk of natural gas pipelines. Shi et al. [49] improved the AHP method by using a fault tree analysis for quantifying the methane explosion in underground coal mines. Ba et al. [80] established an improved AHP to calculate the weight of indicators to assess the corrosion risk of gas pipelines. Zhang et al. [81] used a Fuzzy analytic hierarchy process to assess the risk of coal and gas outbursts in driving face, considering considers the fuzziness and randomness of indexes. As a result, the Fuzzy theory is always used in AHP to deal with the fuzziness and randomness of index data. The subjectivity and accuracy of the analytic hierarchy process limit the practical application in some scenarios. The method relies to a greater extent on the subjective factors of the decision maker and is not suitable for analyzing problems with high accuracy requirements. The analytic hierarchy process will be more deeply integrated with other methods (e.g., neural networks, fuzzy theory) in future research. In addition, to facilitate the use of users, the hierarchical analysis method may be further softwareized to provide a more convenient operation interface and data analysis functions.

3.5.4. Quantitative risk assessment

Quantitative risk assessment (QRA) represents a formal and systematic method using measurable, objective data to determine the probability, loss, and other associated risks. The analysis of this section is aimed at the new and targeted quantitative risk assessment methods developed by scholars and research organizations in the academic field. Yang and Wu [82] conducted a quantitative risk assessment for land use planning of major hazard installations, considering individual risk and societal risk for chlorine storage tanks. Zhang et al. [83] developed a quantitative risk assessment method for comprehensively calculating the risk of natural gas pipeline networks. Li et al. [84] established a QRA method for a gaseous hydrogen refueling station in Shanghai and found that the compressor leak is the main contributor to the station risk. Ma et al. [85] developed a QRA method based on a geographical information system (GIS) for estimating the risk of urban natural gas pipeline networks and identifying high-risk areas. Wu and Chen [86] conducted a QRA for large-scale oil tanks exposed to lightning, obtaining the risk of rim seal fire, local pool fire, and full surface fire and concluding that rim seal fire is the most dangerous scenario. Meng et al. [87] developed a QRA method for dynamically assess the risk induced by leakage on offshore platforms, obtaining the failure probability of safety barriers and different accident scenarios. Zeng et al. [88] established a QRA method for obtaining domino effect risk triggered by flood by combining the fragility model of tanks subject to flood and the domino effect escalation model. Objectivity and predictability are the main strengths of the quantitative risk assessment methodology, and data dependency is subsequently a constraint of the methodology. The results of quantitative risk assessment are highly dependent on the quality and quantity of data. The academic field tends to explore more systematic risk assessment models and methods that combine multiple risk assessment methods to improve accuracy and efficiency.

3.5.5. Fault tree analysis

Fault tree analysis (FTA) refers to a failure analysis in which an undesired state of a system is examined to know how systems can fail and determine the probability of failure or accidents. Fault tree analysis is widely used for system failure analysis in high-risk industries. The method follows a distribution process that visualizes potential failures and assists in identifying design flaws to ensure system reliability. Yin and Lin [89] used an FTA to analyze the causes of gas leakage from pipelines in cities to support decision-making on prevention measures. Wang et al. [90] developed an incident tree analysis (ITA) method based on FTA and Fuzzy logic to analyze traffic accidents. Zhang et al. [91] developed a Fuzzy fault tree analysis based on Fuzzy logic and FTA to enhance the reliability of the data obtained from expert investigation. Peng et al. [92] proposed a timed fault tree analysis by extending traditional fault tree analysis with temporal events and fault characteristics for obtaining the faults that need to be urgently eliminated and the maximum left time for eliminating the root failure to prevent accidents. Meng et al. [93] analyzed unsafe behaviors in fatal gas explosion accidents in underground coal mines in China using an FTA for obtaining the probability and importance degree of unsafe behaviors. Che et al. [94] used FTA for assessing aviation risk, considering human errors caused by mental workload overload. Bian et al. [95] used FTA to comprehensively identify the risk of tripping accidents and then applied BN to model the accident evolution process in transmission lines. Fault tree analysis tends to be conservative in its estimation, so the actual risk may be underestimated, becoming a limiting factor for its development. The current FTA is still mainly based on two-state and static assumptions, while polymorphic and dynamic characteristics are more common in real systems. Therefore, more accurate research of non-monotonic correlation fault trees while ensuring computational speed is an important topic for the future.

3.5.6. Risk index method

The risk index method works in risk assessment mainly by standardizing the weighting and combining the change values of a series of risk indicators to produce a risk index. The risk index represents accident probability and severity and thus can be used in safety risk assessment. He et al. [96] developed a new safety risk index based on overrun frequency and intensity of flight parameters for assessing the risk of flights. Liu et al. [97] proposed a risk index assessment method for analyzing the risk of urban accident disasters consisting of each regional risk. Zhang et al. [91] developed an expert confidence index to determine the basic events of Fuzzy logic to analyze the risk in metro construction. Chen et al. [98] proposed a road risk index with a hierarchical structure and then developed a decision-making system for road safety management. Kang et al. [99] established a risk index system to dynamically evaluate the risk of tunnel disasters, considering geological conditions, gas, and human factors. Hu et al. [100] proposed an improved AHP vulnerability index for assessing water inrush from aquifers by establishing a vulnerability index model. Zhang et al. [52] established six new indexes based on 300 cases of rockburst for assessing rockburst risk in deep mining. The selection of indicators and the determination of weights are key steps involved in risk assessment using the risk index method. These steps are difficult to operate, requiring consideration of various factors such as historical experience and system characteristics. The development of risk control indices is a major trend in the future development of indices, and the academic field is constantly focusing on the optimization research of risk indicators and weights.

3.5.7. ANN

ANN is a data-driven model originating from the biological neural network, which has a powerful pattern recognition and data-fitting ability to realize mapping by self-learning [101]. In recent years, with the development of artificial intelligence (AI) and computer science, ANN has obtained increasing attention in the risk assessment domain. ANN is often used for learning and training large amounts of data in risk assessment, from which features are extracted to discover patterns and predict risks. Zou and Cao [102] applied BP neural network for analyzing the risk of a deep foundation pit. ANN was used to assess the leakage risk of natural gas pipelines in cities based on parameters related to the risk [101]. Yang and Xue [103] developed an ANN model to assess the risk of tunnel operation caused by voids behind lining (VBL) based on numerical simulation data. Shah et al. [104] developed a risk assessment method based on ANN and GIS to estimate the risk of roads. Sarbayev et al. [105] developed an approach for mapping FT into ANN to support the application of ANN in risk assessment, overcoming the limitations of conventional risk assessment methods. Although ANNs have achieved good results on some tasks, their decision-making process is often difficult to explain, limiting the application of ANNs in some fields that require a high degree of interpretability. The design of ANNs continues to evolve towards adaptive learning capabilities, focusing on the interpretability and transparency of the model, and constantly interacting with the environment to achieve more intelligent behavior.

3.5.8. Monte Carlo method

Monte Carlo (MC) method uses repeated random sampling to obtain numerical results, avoiding the computation complexity of analytic methods. The Monte Carlo method has the advantage of being able to transform complex risk assessment problems into computable mathematical problems that take into account uncertainty and stochasticity. As a result, the Monte Carlo method is always used in complex risk computation. Chu et al. [106] used Monte Carlo simulation to model the uncertainty of probability values of fire protection systems and manual intervention based on fire dynamics models. Luo and Hu [107] developed an event sequence diagram model for analyzing risk evolution and used Monte Carlo method to solve the model and identify critical events. Li et al. [108] used Monte Carlo method to solve limit state equations for obtaining submarine pipeline instability probability. He and Weng [43] established a dynamic method for quantifying the risk of domino accidents in the chemical industry based on Monte Carlo simulation. Zhang et al. [109] assessed the risk of instability failure of the earth–rock dams by combining Fuzzy set theory and Monte Carlo simulation. For complex problems or high accuracy requirements, Monte Carlo methods may require large amounts of computational resources. The computation time and convergence speed constrain the practical application of Monte Carlo method. Performance optimization and model improvement of Monte Carlo method in risk assessment analysis become the main research topics in the future.

3.5.9. Risk matrix

A risk matrix is a matrix used for obtaining the level of risk by considering the level of probability or likelihood against the level of consequences [110,111]. The method has the advantage of quickly identifying and assessing risks. Wang and Shen [110] established a risk matrix model for urban natural gas pipelines, obtaining risk grades of different pipeline sections. Lu et al. [14] developed a risk assessment method based on a risk matrix and bow-tie for natural gas pipelines based on failure probability and consequences. Luo et al. [112] used a fishbone diagram to obtain the leakage causes of spherical tanks and then applied a risk matrix to obtain the grade of leakage risk. Guo et al. [113] used a modified risk matrix method for analyzing behavioral risk in the construction industry and found that unsafe behaviors have a great impact on accidents.

3.5.10. Cloud model

A cloud model based on Fuzzy theory and probability statistics is always used to represent the ambiguity and uncertainty of membership in a complex system and convert a qualitative concept into a quantitative representation [114]. Cloud model is effective in dealing with ambiguity and is particularly suitable for scenarios such as risk assessment, which involves a great deal of uncertainty and ambiguity. Guo et al. [79] used a cloud model to transfer the results of experts into the numerical characteristics of a cloud model by using the backward cloud generator for risk assessment of natural gas pipelines. Wang et al. [115] applied a normal cloud generator for risk assessment of rockfall hazards in a tunnel portal section, forming a multi-criteria assessment of the rockfall risk. Li et al. [116] combined the best–worst method (BWM) and cloud model to calculate the weight of each expert to risk factors and assessed each failure mode by cloud distance. Zhang et al. [117] developed a risk assessment method based on a cloud model for coal and gas outbursts, overcoming problems such as fuzziness and index weight deviation.

4. Discussion

According to this review, many research publications in the safety risk assessment domain are published in international journals each year. In China, safety risk assessment has rapidly developed in the recent two decades and it has been applied in different domains such as the traffic domain, hazardous material domain, and mining domain. Besides, we identify 32 risk assessment methods from 1449 publications. With the development of quantitative risk assessment, Bayesian networks Fuzzy theory, and Monte Carlo methods which can be applied for quantifying risk are widely used in different domains. Besides, Analytic Hierarchy Process is also widely used for solving multi-objective decision-making problems based on mathematics and psychology. In this section, possible research issues are discussed to put forward the pathways for future safety risk assessment research in China.

4.1. Dynamic risk assessment

Dynamic risk assessment is proposed for overcoming the limitations that static risk assessment methods cannot grasp the dynamics of unsafe interactions and fail to capture the change of risks over time [9]. Since most systems in the world are dynamic and ever-changing, dynamic risk assessment is better to model time as an influencing factor of risk and the risk can update over time [118]. In that case, risk management can be adjusted dynamically according to the results of dynamic risk assessment. Many traditional risk assessment methods can be improved for capturing the dynamics of risks such as event sequence diagrams (ESDs), dynamic event tree (DET), dynamic fault tree (DFT), dynamic graphs (DG) and dynamic Bayesian network (DBN). Although some of them have been used by Chinese scholars, more attention should be paid to developing new dynamic methods and promoting the application of dynamic risk assessment in the real world to improve safety management in different domains.

4.2. Data-driven risk assessment

Data-driven risk assessment may refer to the risk assessment compelled by data rather than by intuition or personal experience. In the digital age, a large amount of data emerges in different domains in which risk assessment may benefit from these data by using data-driven methods such as ANN and machine learning. Data-driven risk assessment can model highly nonlinear relationships between risk and influencing factors and allows considering many factors, making the assessment results more accurate. In the past years, simple data-driven risk assessment methods such as ANN have been used in the safety domain [101,105], while newly developed methods such as deep learning methods and reinforcement learning may be developed in the future to better model safety risk. In that case, emerging data can be fully used for assessing and predicting risks.

4.3. Risk assessment of digital or autonomous systems

Industry 4.0 and digitalization encompass various new technologies, including the Internet of Things, cyber-physical systems, big data, cloud computing, and AI. The development creates many unmanned/autonomous systems such as unmanned vehicles which can largely reduce the use of labor forces, and increase production efficiency. Besides, the use of advanced technology can produce a large number of data and promote the development of safety risk assessment. However, new risks that emerge from digital or autonomous systems may lead to difficulties in risk assessment. For instance, the safety risk of these systems highly depends on the reliability of the elements in the systems, cyber security may make it difficult to predict the possible risks, and the potential consequences may be more severe in light of cyber-attacks. For example, the attack on an unmanned vehicle system may lead to traffic tie-ups and multiple collision accidents, resulting in massive property losses and casualties. As a result, risk assessments should be improved to adapt to the operation of digital or autonomous systems.

4.4. Risk assessment related to extreme events

Natural hazards are of significant concern for the engineering development of critical infrastructures such as dams, highways, and chemical clusters. Human destructive activities such as greenhouse gas emissions and environmental pollution lead to climate change, resulting in many extreme events such as extreme low-temperature weather, extreme high-temperature weather, and extreme floods. These extreme events may also trigger industrial accidents, aggravating the consequences. However, most of the present risk assessment ignores the scenarios caused by extreme events, which may underestimate the risks, causing immeasurable losses. For instance, an extreme flood may exceed the designed maximum flood discharge capacity of a dam, leading to a dam break, and the dam break may cause the break of other dams in the river, triggering a chain of accidents. As a result, more attention should be paid to risk assessment related to extreme events.

4.5. Research cooperation in the risk assessment domain

Research cooperation is essential for sharing the latest research outcomes and creating new knowledge. However, research cooperation networks in the risk assessment domain in China tend to be geographically concentrated around the most productive authors. There is a lack of academic cooperation between different organizations. The most productive authors always cooperate with scholars in their organizations, lacking cooperation between different organizations. In terms of international cooperation, most of the cooperations are in the domains of hazardous materials and traffic domains, the cooperation in other domains such as structure safety risks should be enhanced. Enhancing academic cooperation and communication in the future may promote the development of risk assessment in China and thus improve the safety management level of China.

5. Conclusions

This study develops a four-step methodology to review the literature related to risk assessment research in China and obtain the current research status and future needs: searching and refining literature based on the Web of Science database, analysis of publications based on bibliometric analysis, thorough analysis of research topics and methods, discussion of future research needs. By the implementation of this methodology, many conclusions are obtained, as follows: (1) The main research domain related to risk assessment includes traffic risk, hazardous material risk, structure, and construction risk, mining risk, energy system risk, and urban risk; (2) The most frequently used research methods related to risk assessment in China are Bayesian network, Fuzzy theory, analytic hierarchy process, fault tree analysis, risk index method, and ANN; (3) The main research organizations consist of China University of Petroleum, Wuhan University of Technology, China University of Mining and Technology, Beijing Jiaotong University, Tsinghua University, etc.; (4) Two members of the Chinese Academy of Engineering (Laibin Zhang and Xinping Yan) play a leading role in risk assessment and two famous international scholars (Faisal Khan and Genserik Reniers) have the most international cooperations with Chinese Scholars; (5) Dynamic risk assessment and data-driven risk assessment need to be further developed in China; (6) More attention in China should be paid to risk assessment of digital or autonomous systems, risk assessment related to extreme events, risk assessment of megacities to develop a safer China. Based on the limitations of bibliometric analysis, this study is unable to cover the in-depth analysis of literature content, unable to timely update research developments due to time delay, and unable to fully take into account literature that has not been published in high-impact journals or academic achievements disseminated through non-traditional channels (e.g., conference reports, blog posts). We will continue to deepen the research in the next step to overcome the above limitations.

Ethics statements

Not applicable because this work does not involve the use of animal or human subjects.

CRediT authorship contribution statement

Chao Chen: Writing – original draft, Resources, Methodology, Formal analysis. **Jiali Tang:** Writing – original draft, Validation. **Jie Li:** Writing – review & editing, Software, Formal analysis, Conceptualization. **Genserik Reniers:** Writing – review & editing, Conceptualization. **Changjun Li:** Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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