1. Introduction

The 1980s marked the emergence of the concept of “big data” when the term was first coined by Toffler (1990). He praised the term as “the wonderful music of the third wave,” but did not give it rich connotations (Yuan, 2019). In June 1999, Mashey (1999), Chief Scientist at Silicon Graphics, presented a paper clarifying the concept of big data titled “Big Data and the Next Wave of InfraStress Problems, Solutions, Opportunities” at the USENIX Annual Technical Conference. On September 4, 2008, Nature published an album named “Big Data,” which discussed the challenges and opportunities of big data from different aspects, such as internet technology, network economics, and bio-medicine. This spurred a discussion on the use of big data in various industries (Lynch, 2008), and the concept has since gradually attracted more public attention. The rapid development of computer and internet technology in the 10 years that followed had continuously digitized data and networks, which brought new connotations to big data and further enhanced its value (Ouyang et al., 2018).

Big data is also sparking a revolution in scientific thinking and methods in the field of safety management (Wang and Wu, 2017), and safety scientists should re-examine the current situation and future development of the field within this context. In recent years, scholars have been conducting research on big data, which undoubtedly reflects its important role in the development and practical application of safety science. At the theoretical level, for example, Wang and Wu (2017) proposed the concept of safety big data (SBD) and systematically discussed its connotation to clarify the influence of big data on the development of safety science. They sought new directions for the research and development of safety science in the context of big data. Additionally, Ouyang et al. (2018) analyzed the rules, methods, and principles of SBD, and proposed the application prospects and challenges of big data to safety science in a theoretical study. At the application level, Shi and Abdel-Aty (2015) studied the application of big data in traffic safety monitoring, while Pollard et al. (2019) discussed its application in food safety and quality. The above examples show that the use of big data is becoming more in demand in safety management (Wang and Wu, 2017) and more scholars are beginning to use big data thinking and methods to carry out research on related problems in the field.

Generally speaking, recording the historical development and research progress of a certain field should serve as the basis in ensuring its scientific development (Wang and Wu, 2020). However, to date, there is still no relevant review on the development process and research progress of big data in safety management, which reduces the possibility of further developing it in the future. To fill these gaps, this study focuses on the history and representative studies of big data in safety management, aiming to help researchers and practitioners have a comprehensive understanding of the research situation in the field. At the same time, we discuss the current limitations, challenges, and research
directions of big data in safety management to lay a foundation for its future development. We hope that this research will encourage safety science scholars to pay more attention to big data technology.

The main framework of this paper is as follows: Section 1 briefly describes the emergence of big data and its development in safety science and presents the main research purpose and overall framework of the study. Section 2 discusses the importance of big data in safety management, including its development, influence on safety management, and its challenges and opportunities. Section 3 elaborates on general theories and technologies of big data in safety management. Section 4 reviews typical applications of big data in different safety management fields, including traffic safety, public safety, chemical safety, construction safety, mine safety, fire safety and occupational health and safety. Section 5 discusses the advantages and limitations of big data in safety management and proposes future research directions. Section 6 summarizes the results.

2. The importance and influence of big data in safety management

The advent of the era of big data has brought a subversive influence on productivity and life. With the broad application of information technology in the field of safety, safety management has become a data-intensive field. Big data will inevitably lead to major changes in safety management (Wang, 2019). This section briefly discusses the importance and influence of big data in safety management.

2.1. The development of big data

When Toffler (1990) first proposed the concept of big data, many industries realized that the improvement of services required more data processing. The amount of data that needed to be processed exceeded the carrying capacity of the main storage, local disk, and even remote disk, resulting in the problem of “massive data” (Wang et al., 2013; Yuan, 2019). However, due to the lack of basic theoretical research and technical innovation ability, the discussion on big data was only a flash in the pan.

The album “Big Data” published by Nature sparked a worldwide discussion on big data (Lynch, 2008), and handling huge amounts of it became an urgent matter. People from all walks of life around the world began to conduct research on big data and apply it in practical settings. The following are typical research and discussions on big data in the development stage:

(1) In the book Beautiful Data (published by O’Reilly Media), Segaran and Hammerbacher (2009) described technologies related to big data, including using them to study urban crime trends, drug research, and DNA-related devices.
(2) In the book The Fourth Paradigm (published by Microsoft Research), Hey (2009) discussed the development of a scientific research paradigm, including four development stages: (i) theoretical science; (ii) experimental science; (iii) computer simulation; and (iv) data science.
(3) Kenneth Cukier published a 14-page special report on big data in The Economist, which systematically analyzed the data problems in society. He confirmed that there is an unimaginable amount of digital information in the world growing at an extremely fast rate (Chen, 2016).
(4) Science published an album called “Dealing with Data,” which discussed the importance of data in scientific research, as well as the opportunities and challenges they present (Science Staff, 2011).
(5) McKinsey Global Institute released a research report named “Big data: The next frontier for innovation, competition, and productivity”, which concluded that the time had come for big data to be integrated into businesses, and its application would be integrated into politics, economy, society, and other fields (Chen, 2016; Sun, 2013).
(6) ERCIM News published a special issue called “Big Data” that discussed data management, data-intensive research, and other issues (Li and Cheng, 2012).
(7) The World Economic Forum released The Global Information Technology Report 2014 under the theme “Rewards and Risks of Big Data,” which argued that policies for all forms of information and communications technology would become even more important in the coming years (Billbaosorrio et al., 2014).

Big data entered the outbreak stage after the year 2012. It became the topic of The Times and was discussed by people from different backgrounds. The cognitive update of data led to a change in thinking, business, and management, prompting a continuous expansion of the scale of applicability of big data. So far, policies, regulations, technology, education, applications, and other development factors related to big data have begun to mature (Yuwan, 2019). The service mode of data utilization runs through all aspects of life, which effectively improves the intelligent level of social development and enhances the ability of public service and safety management.

2.2. The influence of big data on safety management

Big data has an important influence on the development of safety management as a research method and application technology. Although the concept of big data was just put forward in its embryonic stage, the data statistics of accidents and work safety using big data thinking had already gradually emerged. For example:

(1) O’Donnell and Hoy (1981) presented all the steps used to calculate the occupational casualty incidence rates using occupational injury data (including injury, illness, death, and lost working days) and production safety data.
(2) Chong (2002) introduced the application of information database in coal mine safety management, and provided a more intuitive and reliable means for coal mine safety production, scientific command, and correct decision-making through the establishment of a safety information database.
(3) Zheng et al. (2005) provided the assessment process of the risk of city fires using city fire statistics data. They determined the loss rate and surpassing probability after a fire occurred in a city, providing technical reference for city fire planning.
(4) Wu and Yin (2007) analyzed the relevant factors affecting safety data collection channels in the coal mine industry, and recommended countermeasures to establish an open and flat data collection management system.
(5) Sissell and Kara (2007) presented hazard descriptions of common chemicals published by the U.S. Environmental Protection Agency, which included important assessments of the quality and integrity of safety data.

However, due to the limitations of big data technology, the volume of data captured in the embryonic stage is relatively small with less redundancy and a single structure, which only reflects the value of small data for safety events (Huang et al., 2019). In their study, Ouyang and Wu (2016) called these safety-related data safety small data (SSD) and defined it as the set and foundation of SBD.

With the investment of big data in various industries and the maturity of technology application in recent years, many safety-related organizations, departments, and enterprises tried to solve safety problems through the use of big data. For example, Pozzi et al. (2011) studied automatic safety monitoring tools by using big data methods and tools. Xiao et al. (2014) combined theories related to big data with the actual situation of food safety in China to explore the technical framework, system, and potential application value of big data on food safety. Gulijk...
et al. (2015) outlined a research project that examined the important role of the new internet-driven data revolution in safety and risk management for UK rail travel. Compared to the embryonic stage, the research and application of big data has made great progress in promoting safety management during the outbreak stage.

The strategies of various countries also promote the influence of big data in the field of safety management. Since 2012, governments in the United States, United Kingdom, Germany, Japan, China, and other countries have released programmatic documents related to big data (see Table 1). These documents aimed to enhance national core competitiveness by improving social productivity, creating new economic and social values, and maintaining national safety through the implementation of big data strategy. For example, with regards to safety management, China officially released “The Notice of the State Council on Printing and Issuing the Program of Action to Promote the Development of Big Data” on September 5, 2015 (The State Council of the PRC, 2015), which had an extensive influence in society. “The Program of Action to Promote the Development of Big Data” was compiled by the National Development and Reform Commission and the Ministry of Industry and Information Technology after in-depth thematic studies and an extensive solicitation of opinions and suggestions from relevant departments, experts, and scholars. It was the first authoritative and systematic document to promote the top-level design for the development of big data in China from the overall perspective of the national big data development strategy (Shan, 2015).

While big data has greatly enriched the connotation of safety management, as well as provided new ideas and methods, it has also triggered some problems. Some scholars realized that big data is both a challenge and an opportunity for safety management.

The challenge of big data to safety management is mainly manifested in its influence on the traditional safety management paradigm (Huang et al., 2019). First, many existing safety laws are summarized from traditional safety data and only reflect the safety laws of specific statistical samples. Therefore, the applicability of the traditional safety management paradigm will be challenged by massive big data. Second, the traditional safety management paradigm can no longer be effectively applied to complex systems that are constantly changing at any time. Third, most existing accident causation theories are derived from summarizing and refining the law behind the cause of the accident (Goh et al., 2012). However, this safety management paradigm is only applicable to preventing accidents that have happened before. For unknown new accidents, they can be predicted and analyzed using big data. Finally, the most important principle of the traditional safety management paradigm is causal analysis, which is not applicable to the increasingly complex nonlinear safety problems. Big data replaces “causal analysis” with “correlation analysis,” which is a new challenge to the cognition of safety managers and the safety management paradigm.

The opportunity of big data in safety management mainly lies in the innovation and transformation of the concept and method of safety management, which is the first step in its development. We therefore propose three new important concepts and methods of safety management in the era of big data (see Table 2), which present a new understanding and definition of safety management (Wang, 2019).

Big data can pose challenges to some traditional theoretical systems of safety disciplines, such as safety systems, safety ergonomics, safety economics, and safety statistics (Ouyang et al., 2018). Nevertheless, from the perspective of the development of safety science, it can also promote the birth of new disciplines in the future, such as computational safety science (Wang, 2020), and SBD science (Wang and Wu, 2017).

### Table 1

<table>
<thead>
<tr>
<th>No.</th>
<th>Year</th>
<th>Country</th>
<th>Strategic measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2012</td>
<td>The US</td>
<td>The US government released the “Big Data Research and Development Initiative,” which took the lead in making big data a national strategy. It called for greatly improving the ability of the US to extract information and intelligence from massive and complex data sets (Jian and Rui, n.d.).</td>
</tr>
<tr>
<td>3</td>
<td>2013</td>
<td>The UK</td>
<td>The UK government published “Seizing the Data Opportunity—A Strategy for UK Data Capability” (You, 2014). It aimed to enhance the UK's position in the world of data mining and value extraction, and generate more benefits for its citizens, businesses, academic institutions, and the public sector in the information economy.</td>
</tr>
<tr>
<td>4</td>
<td>2013</td>
<td>Australia</td>
<td>The Australian Government Information Management Office released the ‘Public Service Big Data Strategy’ (Liu and Yan, 2014), which aimed to push the public sector to use big data analytics to reform services, develop better public policies, and protect citizens' privacy.</td>
</tr>
<tr>
<td>5</td>
<td>2013</td>
<td>France</td>
<td>In 2013, the French government invested €11.5 million in seven big data market research and development projects, aiming to promote the development of big data in France by creating innovative solutions and putting them into practice (Jin, 2013).</td>
</tr>
<tr>
<td>6</td>
<td>2013</td>
<td>Japan</td>
<td>Japan issued the “Declaration on Building the Most Advanced IT Nation.” The manifesto comprehensively expounded Japan’s new information technology national strategy for the period 2013 to 2020, with the development of open public data and big data as the core. It also proposed to make Japan an information industry society with the highest standards in the world (Jin, 2013).</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>No.</th>
<th>Concept and method</th>
<th>Brief explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Evidence-based safety management</td>
<td>In evidence-based safety management, “evidence” includes data and information, such as safety laws and regulations, standards and specifications, and accident investigation reports, which have shown explosive growth in the era of big data (Wang et al., 2017). In order to effectively utilize large amounts of data and information, the concept and method of evidence-based safety management should be applied to the practice of safety management.</td>
</tr>
<tr>
<td>2</td>
<td>Data-driven safety management</td>
<td>Safety managers use safety information obtained from safety big data to make scientific safety predictions, safety decisions, and safety implementations (You et al., 2018b; Wang et al., 2019a,b). The safety data sources involved in data-driven safety management are more comprehensive than those involved in evidence-based safety management, and the amount of safety data is larger (Wang, 2019). Data-driven safety management can better alleviate and solve the problem of missing information in safety management.</td>
</tr>
<tr>
<td>3</td>
<td>Intelligence-led safety management</td>
<td>The safety data and information collected are processed into safety intelligence, which can be used to support safety decision-making and guide specific actions in safety management (Wang, 2021). Big data technology makes it easier to obtain and analyze safety data and information, which are the raw materials of safety intelligence (Wang and Wang, 2021a).</td>
</tr>
</tbody>
</table>
3. General theories and technologies of big data in safety management

Through analysis and induction, this study divides the theoretical and technical research of big data into five aspects according to different research contents (see Fig. 1): (i) basic theories of safety big data; (ii) big-data-driven safety management; (iii) big-data-driven risk assessment and management; (iv) big data application platform and design scheme in safety fields; and (v) big data-related technology developments in safety fields. This section mainly reviews the above five aspects in detail.

3.1. Basic theories of safety big data

The Chinese government has always attached great importance to the construction of safety science (Wang et al., 2020). Chinese scholars were the first to conduct basic theoretical research on SBD. For example, Ouyang and Wu (2016b) were the first to compare big data with traditional safety data. They put forward the formal term “safety big data” from the perspective of safety science, and achieved a series of related research results. Safety big data is an abstract expression of safety phenomenon, and a new academic concept formed based on the cross fusion of safety and data sciences. Wang and Wu (2017) formally defined SBD during the height of the innovation and development of safety science, and presented the idea of establishing SBD science. More representative researches are shown in Table 3.

Big data is important for the development of safety science (Wang, 2021; Wang and Wu, 2020). At present, safety science has entered the era of big data, on which the frontier research of safety science, “safety information,” and “safety intelligence” are based on. Safety big data has been rapidly developing with the continuous development and integration of big data technology and safety science and technology, which has injected more vitality into safety science research. In addition, big data enriches research ideas and methods on safety science that are especially helpful for the study of macroscopic safety laws. We should believe that SBD science in the context of big data is likely to become a discipline in the future, aiming to reveal the safety laws hiding in big data, and expand the scope of application of SBD in other fields.

3.2. Big-data-driven safety management

Big data is considered to be the most important resource for safety management (Badri et al., 2018; Ding and Li, 2013). It has been having an increasingly important influence on people’s lives through safety management due to the rapid development of science and technology, such as computers, the Internet, and data science in recent years. Both academia and industry have always attached great importance to the construction of “big-data-driven safety management” and made outstanding contributions to it. The study of big data in safety management can provide universal theoretical guidance, countermeasures, and technical applications in various industries. The research in this area mainly includes the architecture, models, and methods in safety management related to big data (see Table 4).

3.3. Big-data-driven risk assessment and forecasting

Big data will undoubtedly bring valuable knowledge to many organizations (Choi et al., 2017). With the arrival of the Industry 4.0 era, the industrial manufacturing system keeps innovating and gradually evolves...
into an intelligent and interconnected production system (Yao et al., 2017; Zhong et al., 2017). However, the industrial system is increasingly complex and poses risks to the system as a whole. In order to cope with the challenges brought by the increasingly competitive market, higher customer demand, and more complex risk management and control, many industries must use big data technology effectively to process and analyze massive data (Niesen et al., 2016). Currently, big data technology is widely used in risk assessment and management in various fields or systems, such as financial risk, engineering risk, medical risk, business operation analysis, and more. For example, Alibaba applied big data to fraud risk management and established a fraud risk monitoring and management system that can accurately predict bad users and forecasting (Chen et al., 2015). The following are typical studies that have been conducted in recent years:

1. Hegde and Rokseth (2020) reviewed the relevant literature on engineering risk assessment with the method of machine learning, bridging the knowledge gap.
2. Nyman et al. (2018) applied an algorithm analysis to a large amount of financial market data and helped assess risks in the financial system through quantitative indicators.
3. Feng et al. (2017) proposed and designed the Intelligent Perioperative System, which can process large volumes of patient data in real time, be used to interact dynamically with physicians, and comprehensively evaluate the surgical risk of patients.
5. Choi et al. (2017) presented the challenges and opportunities of big data analytics in the field of industrial systems engineering and cybernetics, including business operations and risk management in important areas.
6. Goel et al. (2017) discussed the potential of big data analytics in the area of risk management and process safety in the energy industry.
Research on the application platform and design scheme of SBD.

<table>
<thead>
<tr>
<th>No.</th>
<th>Reference</th>
<th>Platform or scheme</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zeng (2014)</td>
<td>Big data platform for monitoring and controlling major hazards dynamically and intelligently</td>
<td>The platform can collect and share mass data on production safety. It can summarize the rules of accident occurrence through a big data analysis model, and realize the delicacy management of major hazard sources.</td>
</tr>
<tr>
<td>2</td>
<td>Guo et al. (2015)</td>
<td>Framework of big data-based behavior observation</td>
<td>The framework includes the establishment of a behavioral risk knowledge base and big data cloud platform, as well as the collection of the unsafe behavior graphs of workers to reduce the negative influence of limited behavior observation on behavior-based safety. In particular, this study has been applied to some construction lines of Wuhan Metro in China.</td>
</tr>
<tr>
<td>3</td>
<td>Xiao et al. (2016)</td>
<td>Big data of food safety and health platform</td>
<td>The platform can solve the problem of information asymmetry among producers, consumers, government regulatory authorities, and other stakeholders in the food supply chain from farm to table and after-meal life, and ensure the safety of all links in the food industry chain.</td>
</tr>
<tr>
<td>4</td>
<td>Guo et al., (2016)</td>
<td>Big Data-based platform for workers’ behavior observation.</td>
<td>The platform was implemented in the construction of the subway system, which can effectively analyze the semantic information contained in the image. It can automatically extract the unsafe behavior of workers, and quickly retrieve it from the Hadoop Distributed File System.</td>
</tr>
<tr>
<td>5</td>
<td>Kverneland et al. (2017)</td>
<td>Max (an industrial data platform)</td>
<td>The platform enables the large-scale collection, aggregation, and analysis of device data in real time to improve performance while reducing maintenance costs for many products and systems.</td>
</tr>
<tr>
<td>6</td>
<td>Zhou (2020)</td>
<td>Industrial safety big data platform based on ultra wide band positioning</td>
<td>The scheme integrates intelligent big data, ultra wide band positioning, IoT, and other technologies to build a big data platform for industrial safety to improve the efficiency of production safety management and reduce accidents.</td>
</tr>
<tr>
<td>7</td>
<td>Jing et al. (2020)</td>
<td>Overall scheme of safety big data application in railway administration</td>
<td>This scheme elaborates on the requirements, objectives, overall architecture, network architecture, functional design, and development trend of the application of SBD in railway administration. It provides ideas for the application construction of SBD in railway administration.</td>
</tr>
<tr>
<td>8</td>
<td>Chen et al. (2021)</td>
<td>Design of railway safety comprehensive management system based on safety big data application platform</td>
<td>Through data mining and analysis, the design scheme can reveal the characteristics and laws of accidents, safety problems, and other hazards from different perspectives. It can provide a new auxiliary decision support for railway safety supervision and management.</td>
</tr>
</tbody>
</table>

Safety and emergency management departments in various countries are also constantly advocating the application of big data in risk assessment and forecasting. Take China as an example, “The 13th Five-Year Plan for National Informatization” (The State Council of the PRC, 2016) and “The 13th Five-Year Plan for Production Safety” (General Office of the State Council 2016). These plans advocate the application and development of big data and intelligent applications in various fields, including the railway industry, food safety, and emergency management, to improve decision-making, risk management, and safety performance.

Research on big data-related technologies in the field of safety.

<table>
<thead>
<tr>
<th>No.</th>
<th>Area</th>
<th>Main research</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Machine learning</td>
<td>Peng et al. (2019) obtained the laboratory safety data of Southwest University, and proposed a new method of laboratory safety management evaluation based on machine learning. In order to solve complex elevator safety management problems, Liu et al. (2010) designed an evaluation method for elevator safety management by machine learning based on the gathered data related to elevator safety status. Using key data from a large contractor in Singapore, Poh et al. (2018) proposed an inspection approach for developing safety regulations and indicators to classify sites according to their safety risk in construction projects.</td>
</tr>
<tr>
<td>2</td>
<td>Artificial intelligence</td>
<td>Rao et al. (2019) designed the artificial intelligence-based big data safety management platform for dyke engineering, which can provide a technical reference for the mining of filling stone materials in dyke projects. Sattari et al. (2021) used artificial intelligence and Bayesian network technology to mine the value of accident data in 8199 accident reports. Guo et al. (2020) summarized the research results of using artificial intelligence to identify birds and looked into the prospect of bird identification technology in airport safety management.</td>
</tr>
<tr>
<td>3</td>
<td>Internet of Things</td>
<td>Zhong et al. (2014) proposed a specific application of the IoT for the construction industry, namely Safety Management System for Tower Crane Groups, which can detect the running state of each tower crane by collecting data from sensors. Chen and Chen (2014) studied the intelligent mobile information platform for coal safety management based on cloud computing and IoT technology. Ma et al. (2018) summarized the research results of the IoT technology in the field of public safety, and emphasized the challenges and opportunities it faced in the application process.</td>
</tr>
<tr>
<td>4</td>
<td>Cloud computing</td>
<td>Zou et al. (2017) proposed a cloud-based safety information and communication system to improve the safety performance of infrastructure projects. Lucas and Whiteside (2015) briefly reviewed the history of process safety and discussed the principles and role of cloud computing in process safety and functional safety in the industry. Xu and Liu (2014) analyzed the characteristics of cloud computing and the status quo of enterprise safety management, and proposed the application solution of cloud computing in the safety management of the China National Offshore Oil Corporation.</td>
</tr>
</tbody>
</table>
Office of the State Council of the PRC, 2017) emphasized the promotion of big data analysis forecast ability to strengthen risk forecasting and assessment, provide information support, and guarantee solutions for major social problems, such as the large number of total production accidents and the fluctuation of extra serious accidents.

3.4. Big data application platform and design scheme in safety management

Since 2016, policies, regulations, technologies, and standards related to big data have gradually matured. Data sharing, linkage, and analysis as the basic form of digital economy and data industry are booming in the global scope. A complete and mature big data industry chain covering data collection, analysis, integration, and application has gradually formed in the market (Yuan, 2019). Some enterprises in safety fields use big data as the core and cloud computing as the basis to participate in work safety supervision and business management. They use advanced technologies, such as the Internet of Things (IoT), mobile Internet, and artificial intelligence to build a service-oriented “intelligent brain for production safety” through unified and centralized data management and intelligent processing of massive information. For example, the Tongding Group developed a big data platform for work safety and a comprehensive management platform for smart safety supervision (Tongding Group, 2019). These platforms were designed to form the “big safety” pattern of comprehensive management through SBD, realize the omni-directional, multi-level, standardized and information-based supervision mode, increase the depth and intensity of safety management, implement the main responsibility of enterprise safety in production, and improve the efficiency of safety management. Google improved Google Flu Trends (a flu trend detection system) by developing big data technology, allowing flu predictions to be a week to 10 days ahead of the Centers for Disease Control and Prevention’s flu notifications. Governments could use the projections of Google Flu Trends to prepare responses in advance to protect the health and safety of their citizens (Cook et al., 2011). More research on the application platform and design scheme of SBD are shown in Table 5. We predict that the application of SBD in enterprises will be more extensive in the future.

3.5. Big data-related technology developments in safety management

In addition to the above content, some frontier technologies related to big data have also been developed in safety fields, such as machine learning, artificial intelligence, IoT, and cloud computing. Some of the representative studies are presented in Table 6.

4. Typical applications of big data in different safety management fields

There is no doubt that the application of big data in the field of safety science predates its theoretical research (Wang and Wu, 2017). Big data is rapidly developing in all areas of safety management. For example, Walker and Strathie (2016) proposed a new paradigm to deal with strategic transport safety risks through big data and ergonomic methods.
Zhou and He (2017) proposed to strengthen the innovation of the urban public safety emergency management system through the idea, method, and technology of big data. Tan et al. (2016) proposed to utilize big data to manage safety risks in the upstream oil and gas industry and improve its injury and fatality statistics.

In addition, big data has also provided important evidence for accident accountability (Huang et al., 2018a; Wang et al., 2017). One example of this would be the mine disaster that killed 29 people in West Virginia, United States. Because of the integrity of the mine’s regulatory records, each record included the time of inspection, results, legal provisions violated, opinions handled, number of fines, amount of money paid, and whether the coal mine appealed. With the help of big data, the coal mine safety and health bureau were finally determined to be free from supervision and dereliction of duty, and the company belonging to the accident coal mine should be held accountable (Xu, 2010; Zhang, 2015).

The various applications of big data in safety mainly focus on traffic safety, food safety and medicine safety on traffic safety, public safety, and chemical safety. This chapter will review the research and application of big data in different fields by industry classification (see Fig. 2).

### 4.1. Traffic safety

With the development of the urban road traffic network, realizing fine and intelligent road traffic safety management has become an important goal in modern urban management (Wang and Wang, 2021). Below are examples of research on big data in road traffic that mainly focus on technical fields, such as intelligent transportation systems, real-time data transmissions, algorithms, and frameworks:

1. Lian et al. (2020) reviewed recent studies using big data to analyze traffic safety. They believed that traffic big data surpassed the limitations of traditional data analysis and could solve many problems that traditional data analysis could not.
2. Shi and Abdel-Aty (2015) discussed the importance of big data generated by the intelligent transportation system to traffic safety management and confirmed the feasibility of a real-time traffic monitoring strategy.
3. Stylianou et al. (2019) introduced the role of big data in traffic safety analysis, and described the latest real-time crash prediction studies and other related technologies, reflecting the new perspective of big data application in road safety analysis.
4. So et al. (2019) proposed a crash scene reconstruction method based on big data technology. The authors provided a systematic and effective method for the development of automated vehicle critical traffic safety test scenarios.
5. Amin et al. (2019) proposed that intelligent transportation facilities would generate a large amount of data, and discussed the role of big data in shaping intelligent transportation systems, with focus on road safety.
6. Chong and Sung (2015) investigated actual cases of road management systems in some countries and analyzed the types and feasibility of road safety prediction technology based on big data.
7. Hoffmann and Hitscherich (2014) proposed the improvement of the intellectualization of road safety by taking historical and commercial speed data within the scope of the network as a big data source.
8. Tarrahi and Shadravan (2016) proposed a powerful health, safety, and environment management system (HSE) big data analysis platform and specifically introduced how the relevant algorithms can guarantee the occupational safety of technicians and operators in the oil and gas industry.

While there have been representative studies in recent years, theoretical research on big data in road traffic safety remains limited. In addition to the improvement of technology, road traffic safety management also needs the support of society, policy, and law, among other aspects. We need to understand the relationship between these aspects, study the road traffic safety management of a city or a region from a more systematic perspective, and build a large-scale road traffic safety system (Zhang and Song, 2020). Therefore, it is necessary to use innovation as the driving force and strengthen the application of big data in road traffic safety from all levels to effectively improve the level of road traffic management in the context of big data.

### 4.2. Public safety

The traditional public safety management system has been unable to keep up with the rapid pace of urban development in cities (Zhou and He, 2018). With the advent of the era of big data, new elements, such as big data analysis, big data decision-making, and big data management, have been injected into public safety management to give full play to the unique advantages of big data. Because public safety is a major concern, the academe has been conducting extensive research on big data in this field in recent years.

In terms of theory, the research mainly focuses on the numerous problems and countermeasures faced by public safety management in the era of big data. Lee and Kim (2017) reviewed the research trends of 75 big data studies in the field of public safety and found changes in the proportion of different research directions. Zhou and He (2017) proposed solutions to the challenges faced by urban public safety management in the era of big data, such as building a new data government and creating an open data platform. Lu et al. (2020) discussed the definition of social public safety in the era of big data, and proposed the necessity of early warnings for social public safety. Huang et al. (2017) discussed the classification, storage, and sharing of big data for urban public safety, and advocated the establishment of a set of management mechanisms, a big data center, a set of standards and norms, and a platform architecture. Song (2015) established a data-oriented public safety early warning system based on policy and organizational theory, which could produce active early warning and positive linkage effects, thus guaranteeing urban public safety. Zhang et al. (2017) described the process of public safety emergency services, the source and transmission direction of big data, and proposed various applications of big data in emergency services. Its main application in technology is the creation of a variety of big data technology platforms to study public safety. Chen et al. (2016) proposed a big data integrated modeling method for urban population distribution and a real-time big data-driven public safety scenario deduction system framework. Bilili et al. (2017) proposed a framework that integrates data, networks, and technology to create a special platform for big data related to public and personal safety. Kwon and Jeong (2019) constructed a big data platform according to the model which provides electrical public safety services by collecting, linking, storing, processing, and analyzing information related to electrical safety and emergency response. Turet and Costa (2018) analyzed the public safety situation in northeastern Brazil and proposed a decision-making model based on big data analysis.

At present, public safety management in the era of big data still faces many challenges. For example, the use of big data technology to process public safety data is costly, and may not be able to achieve great benefits (Zhao, 2021). Moreover, the government needs to obtain sufficient big data on public safety to guarantee public safety. However, this may raise issues of data privacy since the openness and privacy of data are contradictory (Jiang, 2020). The public will certainly suffer serious losses once collected public data are damaged due to their increasing reliance on data information, undoubtedly posing a threat to public safety (Shi et al., 2021). Therefore, more solutions need to be developed to improve the application of big data in public safety management.

### 4.3. Chemical safety

The production capacity and scale of the chemical industry are
increasing year by year. The operating environment of the industry is especially characterized by high temperatures, high pressure, continuous operation, toxicity, and harmfulness (Hao, 2020; Huang and Liu, 2014). Chemical production and storage facilities are also becoming increasingly complex and large-scale, resulting in a rise in major sources of risk. All kinds of dangerous sources, system defects, equipment safety risks, staff violations and procedures omission will cause serious accidents, resulting in heavy losses (Li, 2016). Nowadays, the rapid development of computer and big data technology has laid an important foundation for the modern monitoring and management of the chemical safety state. Below are some typical studies on big data in the field of chemical safety:

(1) Based on the big data analysis of hazardous chemical accidents, Wang and Zhao (2016) put forward some suggestions for chemical safety management from the perspective of system and mechanism.
(2) Ji et al. (2020) reviewed and looked forward to the development of industrial big data and its application in the chemical industry.
(3) Reis and Saraiva (2019) proposed the shifting of the chemical industry to a new paradigm of “Industry 4.0” centered on data to solve the current problems related to chemical process safety.
(4) Saba (2017) showed that investment in big data and analytics has brought tremendous benefits to organizations in the Indian chemical industry.
(5) Hu et al. (2021) provided countermeasures for chemical safety driven by intelligent technology to escort production safety.
(6) Ban et al. (2020) studied the construction of the innovative application system of critical chemical safety supervision based on the big data of the Beidou positioning system and on the investigation of critical chemical enterprises’ emergency management.
(7) Belaud et al. (2014) proposed an open platform for collaborative simulation and scientific big data analysis, and illustrated various situations and challenges of chemical process engineering and natural disaster management.
(8) Shu et al. (2016) proposed a new framework based on the big data in a cloud computing environment of a big chemical corporation to solve the challenging problems in abnormal situation management.
(9) Yao (2016) proposed the establishment of a big data management platform on the basis of a study on the health and traffic safety of professional logistics transportation drivers.

With the improvement of the safety management system of large chemical enterprises and the continuous promotion of the internet application, a large amount of data has been accumulated for safety management. Data is being utilized to analyze the occurrence of accidents caused by unsafe behaviors and environments. However, while many chemical enterprises rely on computer control systems to carry out the real-time monitoring of production safety using data, the utilization and deeper mining of the information behind the data are far from sufficient (Li, 2016) and are worthy of further research.

4.4. Construction safety

With the diversification of construction projects, construction technology is becoming more complex, and people are paying more attention to the quality and safety of construction. Shuai and Li (2013) believe that the main problems in traditional safety management of construction enterprises in China include: (i) workers lack of safety consciousness; (ii) imperfect safety training system; (iii) construction enterprises lacking in safety management and supervision; and (4) inadequate safety budget in construction safety management. It is necessary to apply big data related technologies to construction projects to ensure construction safety, which is a worldwide issue and an important component of smart and safe cities (Li, 2015).

Wang (2016) proposed that a big data platform for construction safety should be established to obtain and collect a variety of data (such as seismic, meteorological, and environmental data) and provide data services. Wu (2019) discussed the application of big data in bridge construction safety and the bottleneck problems encountered, and built a bridge construction safety early warning system. Liang et al. (2021) proposed the framework of using big data technology for construction safety risk management, providing guidance for risk prevention and controlling construction projects. Yi and Wu (2020) reviewed the application of safety management in construction projects through a combination of artificial intelligence and big data, summarized the current development trend, and proposed a safety management design based on big data. Li (2015) reviewed some problems with big data based on the example of the building safety index. Du et al. (2018) proposed a new data service system supported by big data, using data association technology and the New Austrian Tunneling Method to improve the accuracy of predicting accidents and dangerous situations and guaranteeing the safety of underground construction. In view of the shortcomings of construction and safety management in current traditional projects, Liu et al. (2019) proposed the idea of applying big data intelligent manufacturing to the construction industry.

4.5. Mine safety

As in other fields, big data technology has brought new solutions and working methods to mine safety management, which have been discussed by some experts (Li, 2019; Nie and Sun, 2019; Zhang, 2017). First, big data in mining has become more accessible. With the increasingly high level of comprehensive information and extensive application of IoT in the mining industry, low-cost open source data has become an important source to obtain big data (Nie and Sun, 2019). The transmission and sharing of data also improve the utilization of information. Second, big data in mining is easy to store. Cloud computing technology provides a high-quality storage carrier for mine big data, which compensates for deficiencies in traditional computer technology. The application of cloud computing fully embodies the value of big data in mining and lays a data foundation for the safety of mine production (Zhang, 2017). Finally, big data in mining provides a reliable and comprehensive support for mine production safety. It can provide data support for scientific and reasonable decision-making through the professional information processing of mass data and construction of a reasonable data model (Li, 2019).

Ma et al. (2014) studied the role and status of the IoT, big data, and cloud computing in guaranteeing of coal mine production safety, and discussed their relationship in coal mine production safety management. Bychkov et al. (2016) discussed the application of mining information and big data in the comprehensive safety monitoring of subsoil management. Du et al. (2020) proposed the architecture of an intelligent coal mine big data platform and studied the key technologies of data processing. Zhao et al. (2015) discussed a series of issues, such as the necessity of big data application for tailings. Cheskidov et al. (2018) believed that information technology and big data promote the design, application, and management of the mining industry to a higher level, and that data monitoring acted as the key tool in the mining process. Baek and Choi (2019) used big data created by the information and communications technology-based mine safety management system to simulate truck transportation operations. They found that the simulation results became more reliable with an increase in data accumulation time.

4.6. Fire safety

There are many types and huge volumes of data on fire safety. The conclusions drawn through big data analysis are more authentic and instructive. Data sources in firefighting work are mainly divided into
Existing sources of data for fire fighting.

<table>
<thead>
<tr>
<th>No.</th>
<th>Data types</th>
<th>Specific data Sources (some examples)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Own data</td>
<td>Fire alarm system, Fire statistical management system,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fire hazard information system, Fire supervision and management system</td>
</tr>
<tr>
<td>2</td>
<td>Science and technology data</td>
<td>IoT remote monitoring system for firefighting facilities,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electrical fire monitoring system, Freestanding smoke fire detection alarm</td>
</tr>
<tr>
<td>3</td>
<td>Government data</td>
<td>Meteorological data, Urban road planning data, Logistics and migration data, Data on building structure and use properties, Population residence attribute data</td>
</tr>
</tbody>
</table>

Table 8

Advantages of big data in safety management compared with traditional data.

<table>
<thead>
<tr>
<th>Items</th>
<th>Traditional data</th>
<th>Big data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data sources</td>
<td>Traditional data are mainly recorded manually, and seldom collected automatically by machines.</td>
<td>Big data mainly relies on user-generated content, and all big data in safety management (such as safety behavior data captured by the platform) are recorded in real time by the machine.</td>
</tr>
<tr>
<td>Data type</td>
<td>The data types of traditional data are single, mainly structural data (such as statistics form of safety accidents).</td>
<td>Big data has a variety of data types that are mainly multivariate, including semi-structured and unstructured data (such as photos and videos obtained by safety monitoring).</td>
</tr>
<tr>
<td>Data processing speed</td>
<td>The traditional data collection, processing, and transmission speed is slow, and the ability of sharing is weak.</td>
<td>Big data can be generated at the millisecond level, showing a geometric growth trend.</td>
</tr>
<tr>
<td>Data value</td>
<td>Traditional data has too much result data and too little process data, so the mining value is low.</td>
<td>Big data has a lot of result data and process data, so the mining value is great (such as online shopping user data).</td>
</tr>
<tr>
<td>Data analysis way</td>
<td>Traditional data focuses on causal analysis, addressing the “whys.” Addressing the “whys.”</td>
<td>Big data focuses on correlation analysis, addressing the “what.”</td>
</tr>
<tr>
<td>Requirements for data analysis results</td>
<td>Traditional data requires an accurate solution and prediction model.</td>
<td>Big data requires an approximate solution and fuzzy prediction model.</td>
</tr>
</tbody>
</table>

3. Occupancy and safety

In the Industry 4.0 era, new paradigm shifts will have an influence on the management of occupational health and safety (Badri et al., 2018). Therefore, avoiding the conflict between technological progress and occupational health and safety is an essential part of promoting the development of Industry 4.0. Culture, risk management, and human factors are key factors in occupational safety management (Costa and Costa, 2020). Below is a list of scholars who have conducted studies on occupational health and safety in the context of big data from different perspectives:

4.7. Occupational health and safety

In the Industry 4.0 era, new paradigm shifts will have an influence on the management of occupational health and safety (Badri et al., 2018). Therefore, avoiding the conflict between technological progress and occupational health and safety is an essential part of promoting the development of Industry 4.0. Culture, risk management, and human factors are key factors in occupational safety management (Costa and Costa, 2020). Below is a list of scholars who have conducted studies on occupational health and safety in the context of big data from different perspectives:

- Li (2013) discussed the proposal, development, and characteristics of big data, and initially suggested the application of big data in the field of occupational safety and health.
- Maugard et al. (2018a) studied occupational risks in agriculture using the French medical management database.
- Maugard et al. (2018b) developed an innovative data mining method to identify the relationship between long-term diseases and occupational activities in collaboration with the French Agency for Food, Environmental and Occupational Health and Safety.
- Badri et al. (2018) believed that previous gains in the preventive management of occupational health and safety would be placed at significant risk with the advent of Industry 4.0. They advocated that researchers, field experts, and industrialists should collaborate to smooth the transition to Industry 4.0.
- Stieb et al. (2017) proposed that big data could provide important information for occupational and environmental health.
- Lv (2019) explored the prevention and control approaches of occupational safety and health risks of traffic police under the background of big data based on its application in the field of safety management through literature research, field investigation, questionnaire survey, and other methods.

Big data will undoubtedly have a huge influence on statistical surveys and information construction in occupational safety and health. While it can address issues in the field that could not be solved in the era of small data, it is still challenging to optimize big data technology and give full play to its role. For example, data on occupational safety and health are now largely distributed across regions and sectors. Therefore, interconnection and information sharing should not only be realized at the technical level, but also at the institutional and mechanism level should information barriers between departments and regions be broken (Li, 2013). In addition, due to the complexity and particularity of data in the field of occupational safety and health, collaborative file systems with multiple technologies are needed to provide support to the lowest
level storage capacity (Lv, 2019).

5. Discussions

We have learned from the above chapters that the application of big data in safety management has gained more attention, developed rapidly, and produced more research results in recent years. Combined with previous studies (Ouyang et al., 2018), we found that the application of big data in safety management has many unique advantages compared with traditional data (see Table 8). However, the application of big data also has its drawbacks. Some of its limitations lie in the field of safety management. We discuss them from multiple perspectives and briefly present future directions for its development. The limitations of big data in safety management mainly include the following six points:

1. The volume of big data is small and the quality is not high. Although safety departments and related enterprises have a certain scale of safety data, these problems still exist. The main reasons behind this are as follows: (i) the insufficient ability to collect big data leads to incomplete original data collection and lack of dynamic data; and (ii) the lack of integration ability of big data leads to defects in comprehensiveness and the standardization of the data itself.

2. There is a lack of standards for big data in safety management. The lack of unified data interaction standard makes it difficult for the system to connect and the safety data to interact. For example, the business processes of various industries, such as construction, transportation, railway, and aviation are different, and the forms of big data obtained are also different, leading to broad limitations of big data convergence.

3. Big data lacks efficient analysis tools. When big data is obtained, it is necessary to transform it into valuable safety information (or safety intelligence) to support safety management through analysis tools (Wang and Wang, 2021b). However, there is still a lack of data analysis tools combined with safety knowledge, resulting in the inability to effectively use big data.

4. Big data professionals are relatively rare. Every link of big data construction needs to rely on professionals to be completed. In particular, big data in safety management needs to prevent safety incidents using future trend analysis, while traditional data analysts generally do not have knowledge and skills in safety, and also lack imagination.

5. Big data has low value density and poor timeliness in terms of safety. The vast majority of big data is structured, while the proportion of non-structured data is very small, leading to a small range of mining. Due to the limitations of sensors and other IoT technologies, some data exchanges need to rely on manual transmissions, which cannot be synchronized in real time, resulting in poor timeliness.

6. The basic environment of big data in safety application is weak. So far, the data volume of various industries has been very large, but only a few enterprises or departments have applied big data to solve safety problems. In addition, the number of relevant safety databases established by governments or enterprises is also extremely limited. The application of big data in safety management is still facing many difficulties in social promotion.

The future development of big data in safety management can be discussed from the perspectives of theoretical research (mainly discipline development) and practical application. In terms of theoretical research, the main development direction of big data is to enrich the connotation of safety scientific theories (Wang and Wu, 2020). Safety science is a typical cross science. Big data has developed new ideas, methods, and perspectives relative to the traditional safety science methodology, which has a profound influence on the study of safety science (Huang et al., 2019). Big data in safety management research involves information science, engineering science, statistics science, among others. The integration of different disciplines and big data will lead to the development and innovation of many safety sub-disciplines. Ouyang et al. (2018) combined big data with safety science theories and proposed the following safety sub-disciplines: (i) basic theory research on work safety; (ii) research on typical accident mechanism, dynamic evolution process and control; (iii) theory research on safety economy; (iv) theory research on safety ergonomics; (v) theory research on safety systems; (vi) theory research on safety sociology; (vii) research on safety information and information security; and (viii) research on safety statistics. In addition, safety intelligence has gradually been attracting the attention of safety scientists, such as Wang and Wu (2018), since 2018. The use of big data to obtain safety intelligence is being emphasized, and researchers have also obtained a series of academic achievements in this field. It is bound to be the next important research area of big data in safety management.

In terms of practical application, big data in safety management needs to be improved in the following five aspects to provide an early warning for the prevention of various safety incidents:

1. The service model of big data in safety management should be transformed from application-centric to data-centric. The previous model built a set of data for each application. In the future, we should build a big data platform to carry different applications.

2. The service objects of big data in safety management should be further extended. Its main service users should include government supervision departments, production and management enterprises, intermediary service organizations, and the public.

3. Research on big data in humanities and the social sciences should be strengthened since big data has mainly been applied in the field of safety technology, that is, the field of natural science. We need to study the influence of big data on the safety of human society systematically and comprehensively from the perspective of the humanities and social sciences (e.g., big data and related laws, systems, and policies) to promote the application of big data in safety management.

4. To protect privacy, access to and sharing of big data in safety management should be limited to a certain extent. We should face the data privacy controversy in a constructive manner and formulate strict rules to avoid the risks that come with big data privacy.

5. Big data should promote the development of artificial intelligence in the field of safety, which will help push human beings into an intelligent safety society (An et al., 2016). For example, an intelligent occupational health safety system can be built with the help of occupational health big data. The food safety situation of the whole process can be obtained through big data. The comprehensive construction of smart cities can be promoted by using big data on urban safety.

6. Conclusions

Big data is an important basis for improving safety and promoting safety management. This study focuses on reviewing the development and research process of big data in safety management, aiming to provide a reference for the further development of big data in the field of safety science. Based on a literature review and other methods, we reviewed the following contents:

1. By combing through the development history of big data, we analyzed its influence on safety management in the development process. We further highlighted the challenges and opportunities faced by big data in safety knowledge.

2. We reviewed the general theories and technologies of big data in the field of safety management, including five aspects: (i) basic
theories of safety big data; (ii) big-data-driven safety management; (iii) big-data-driven risk assessment and management; (iv) big data application platform and design scheme in safety fields; and (v) big data-related technology developments in safety fields. (3) We reviewed the typical applications of big data in the field of safety management according to different industry categories, including seven common industries: (i) traffic safety; (ii) public safety; (iii) chemical safety; (iv) construction safety; (v) mine safety; (vi) fire safety; and (vii) occupational health and safety. (4) We discussed the advantages and limitations of big data in safety management and proposed improvement methods and future development directions.

In addition, the development of big data in safety management needs to be driven by the following four aspects: (i) the accumulation of safety-related theories is the cornerstone of the development of big data; (ii) safety-related technological innovation is the driving force to break through the bottleneck of big data; (iii) safety-related policy support is the external condition for the practical application of big data; and (iv) safety-related demand guidance is the future direction of the development of big data (see Fig. 3). Therefore, we should utilize important opportunities in the development of big data, promote its healthy development in safety management and related industries, and address various issues in a scientific, reasonable, and positive manner.

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.

Acknowledgements

The authors would like to thank reviewers and editors cordially for their positive and constructive comments and suggestions. This study is supported by the National Social Science Fund of China (No. 20&ZD120).

References


