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Chemical industry in China: The current status, safety problems, and pathways for future sustainable development

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ABSTRACT

Safety risks have become an obstacle to the sustainability of the chemical industry in China since many chemical companies were forced to close down by China's government in the past three years. This study investigates chemical safety in China in order to identify the causes of the major accidents and accompanying casualties, formulating the safety management needs to develop a sustainable chemical industry in China. First, we analyze the evolution and current status of China's chemical industry to identify possible safety issues rooted in the industry. Second, a thorough accident investigation is conducted based on official statistics and collected chemical accidents in China in the period 2004–2019. Furtherly, the main laws, regulations, guidelines, standards and measures related to chemical safety are analyzed and compared with those in Europe. According to analyses related to the chemical industry, chemical accidents and safety legislation and measures in China and Europe, the current problems with respect to chemical safety in China are discussed systematically. Based on research findings, we propose recommendations for the improvement of chemical safety so as to promote the sustainable development of the chemical industry in China. This study also provides basic data and information for future studies on the safety and sustainability of the chemical industry and major accident prevention in other countries.

1. Introduction

China's chemical industry (around $1.5 trillion of sales in 2017) has been the largest in the world in view of revenue since 2011, contributing half of the growth of the world chemical market over the past two decades (Hong et al., 2019). Although the chemical industry started much later in China than in Europe, there were about 23,366 companies in China at the end of 2017 according to the report from the Emerging Markets Information Service (EMIS, 2019). The development of the chemical industry has thus provided an important impetus for China's high economic growth in recent decades, creating and maintaining modern-day life for 1.4 billion Chinese people as well as for people around the world. However, the chemical industry and its rapid growth also bring many negative problems, such as safety problems, pollution problems, ecological and environmental problems, high energy consumption, excess manufacturing capacity, etc.

Chemical plants consisting of hundreds and sometimes thousands of hazardous installations situated next to each other are usually characterized by high complexity and interdependencies (Cozzani et al., 2005; Reniers and Cozzani, 2013; Chen et al., 2019a; Zeng et al., 2019). These installations which store, transport, or process hazardous (e.g., flammable, explosive, toxic) substances are usually in high-temperature high-pressure conditions. As a result, a primary undesired scenario (e.g., a loss of containment) may lead to major accidents[1]. Moreover, these primary accidents may propagate to nearby installations, triggering a chain of accidents, resulting in overall consequences more severe than those of the primary event, a phenomenon which is well known as knock-on effects or domino effects (Reniers and Cozzani, 2013; Chen et al., 2018; Chen et al., 2019b). Once a major accident occurs in a chemical industrial area, it may result in huge property losses, casualties, severe environmental pollution as well as ecological and ethical problems (Yang et al., 2018; Yang et al., 2019; Chen et al., 2020).

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[1] Major accident is defined by the Seveso Directive as "an undesired event such as a major emission, fire or explosion induced by uncontrolled developments in the course of an industrial activity, resulting in a serious danger to humans, immediate or delayed, inside or outside the establishment, and/or to the environment, and involving one or more dangerous substances".

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Although the Chinese central government and local governments have already enacted a series of regulations and technical recommendations and taken a lot of other measures to improve chemical safety in China (Wang et al., 2018a; Wang et al., 2018b), the fact of an increased accident risk with the growth of chemical industrial clusters can not be neglected in terms of frequent major accidents. Most recently for instance, on March 21, 2019, a series of explosions and fires at the Jiangsu Tianjiayi Chemical Company, China, almost completely destroyed this chemical plant, resulting in at least 78 deaths, 640 injuries and huge property loss (The State Council, 2019). According to the report of the Department for the Safety, Supervision and Management of Hazardous Chemicals (DSSMHC), 620 chemical accidents occurred from 2016 to 2018 in China and resulted in 728 deaths (DSSMHC, 2019).

To understand the mechanisms, causes, damage potential and likelihood of accidents and to develop accident prevention and mitigation strategies, it is essential to learn from the industry, from past accidents and safety legislation. Liu et al. (2005) analyzed industrial accidents in China using statistical methods in order to predict the accident trend in the future. Yang et al. (2010) analyzed the hazardous materials accidents during road transport in China from 2000 to 2008. The accidents related to hazardous chemicals in China from 2000 to 2010 were also investigated (Duan et al., 2011; Sun and Yang, 2011; Zhang and Zheng, 2012). Zhao et al. (2014) analyzed process safety management in China and demonstrated that insufficient safety management in hazard analysis, training and emergency response planning contribute to most of the accidents in small and medium-sized enterprises in China. China's chemical industry has been the largest in the world in terms of the output value and there are more than 600 chemical industrial parks in China. However, no accident investigation focused on the accidents that occurred in chemical plants and chemical clusters (e.g., domino effects), and there is a lack of a systematic analysis of chemical safety in China: accident causes, current problems and future needs for the sustainability of the chemical industry in China.

Therefore, this study aims to systematically investigate the chemical industry, past major accidents from 2004 to 2019, related safety regulations and technical recommendations in China, to find out the possible safety problems which block the sustainability of China's chemical industry. The research questions are as follows: (i) Why are so many major accidents occurring in China? (ii) Why are so many casualties caused by major accidents in China? and (iii) What are possible future pathways of sustainable development of the chemical industry in China? Based on the research findings, this study provides suggestions for future safety management and sustainable development in the chemical industry within China and therefore for other countries with a quickly developing chemical industry. Indeed, the study on the chemical safety in China can reflect the safety status of chemical industries in developing countries, and the lessons learned from China may even be able to improve the safety and sustainability of the chemical industry all over the world.

2. Methodology

A systemic methodology is proposed to investigate chemical sustainability in China in terms of chemical safety, identifying the current status, safety problems, and future needs. The procedure of the developed 4-step methodology is shown in Fig. 1.

2.1. Step 1:Overview of China's chemical industry

According to the methodology, the first step is to investigate the current status and the evolution of China's chemical industry. The investigation includes the outputs, profits and employees of the chemical industry in China, the number of chemical industrial parks and chemical companies in China, the distribution of chemical industrial areas in different regions of China, and also the evolution of China's chemical industry in recent years. The data and information for this investigation are mainly obtained from authoritative institutions, such as the EMIS, McKinsey & Company, Oxford Economics as well as official statistical agencies in China. Based on the analysis in Step 1, we expect to find out possible safety issues and trends rooted in the industry. More details and results of Step 1 are illustrated in Section 3.

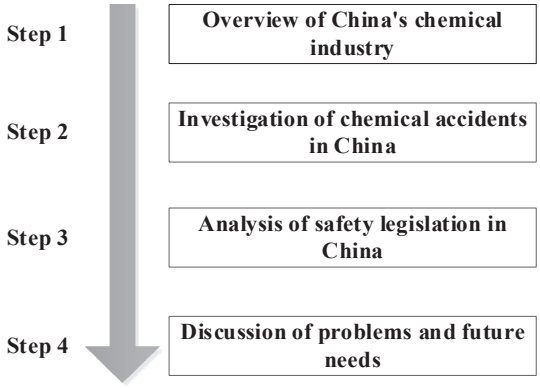

Fig. 1. A systematic methodology for investigating chemical safety in China.

2.2. Step 2: Investigation of chemical accidents in China

Step 2 of the methodology aims to analyze the chemical accidents which occurred in China, with a focus on major accidents. The investigation is divided into two parts. An overview of chemical accidents in China is conducted in part 1 based on the official statistics published by the Ministry of Emergency Management (MEM) of the People's Republic of China (PRC) from 2004 to 2018. The State Administration of Work Safety (SAWS) [2]of PRC started individually collected accidents related to hazardous materials in 2004). The contents of statistical analysis include (i) the evolution of chemical accidents and fatalities over time, (ii) the distribution of accidents and fatalities by different accident levels, (iii) the distribution of accidents and fatalities by province, (iv) the accident distribution by company scales. To provide a thorough analysis of chemical accidents in China, we will conduct a cause-consequence analysis based on the accident data with details from 2004 to 2019. Accident data and information are collected from official accident investigation reports from the Ministry of Emergency Management of PRC and the sub-level offices, the database of China Chemical Safety Association, the database of Petrochemical Accident Analysis and Data Interpretation Platform, etc. First, all the collected accidents are characterized according to scenario types, accident causes, accident origins, hazardous chemicals. Then the distribution of accidents by scenario types, accident causes, accident origins, hazardous chemicals are analyzed. Finally, a fishbone diagram is developed for analyzing more detail the causes of chemical accidents in China. The results of Step 2 are revealed in Section 4.

2.3. Step 3: Analysis of Chinese safety legislation

Obviously, a country's safety level also depends on the safety policy of the country. Step 3 of this methodology, therefore, is to analyze China's safety laws, regulations, guidelines, standards related to chemical safety. First, we will analyze the main national laws and

[2] The Ministry of Emergency Management of People's Republic of China was established in 2018, taking over the responsibilities of the former State Administration of Work Safety and other ministries, including firefighting from the Ministry of Public Security, disaster relief from the Ministry of Civil Affairs, geological disaster prevention from the Ministry of Land and Resources, drought and flood control from the Ministry of Water Resources and prairie fire control from the Ministry of Agriculture.

regulations related to chemical safety issued by the Standing Committee of National People's Congress (NPCSC), the State Council of the People's Republic of China, and the SAWS. Next, these standards and guidelines for safety management of hazardous substances and chemical industrial areas will be investigated. Finally, a comparative analysis of safety policies will be conducted between China and Europe, to find out the differences between China and a region in the world, Europe, where process safety has a history since the 1960s. The detailed results of the analysis are illustrated in Section 5.

2.4. Step 4: Discussion of future needs in terms of chemical safety in China

Finally, a critical discussion on China's chemical safety and sustainability based on the analyses in Steps 1–3, will be carried out to answer the research questions proposed in Section 1. The lessons learned from China can support the decision-making on chemical safety and sustainable development of the Chinese chemical industry.

3. An overview of the chemical industry in China

The output of the chemical industry in China reached $1.5 trillion in 2017, accounting for nearly 40% of global chemical-industry output (Hong et al., 2019). Fig. 2 shows the GDP contributions and jobs supported by chemical industries in China, Asia-Pacific (exclude China), North America, Europe, North America, Latin America & the Caribbean, and Africa & Middle East in 2017. China's chemical industry not only contributes most to the GDP but also supports most jobs all over the world. For example, the number of jobs supported by the chemical industry in China is over 4 times that of Europe. Conversely, the number of companies in the European Union (28,329 companies in the EU at the end of 2017) (Kiss, 2019) is greater than that in China (23,366 companies at the end of 2017) (EMIS, 2019). As a result, the number of jobs per chemical company in China is far more than that in Europe. Once a major accident occurs in a Chinese company, it may thus result in more casualties than that in Europe. The number of chemical companies decreased slightly in recent three years since China closed companies with a high safety risk. This decreasing trend will continue due to recent large accidents in China (EMIS, 2019). The total profit largely increased from 2015, which may urge chemical companies to increase production while may ignore the importance of safety. This may be one of the reasons why chemical accidents in the last three years are at a high level (620 chemical accidents occurred in the period 2016–2018 and resulted in 728 deaths).

In order to obtain scale benefits, exchange material streams, optimize energy streams and manage centrally, chemical clusters or so-called chemical industrial parks have formed in China since the 1990s. Fig. 3 shows the distribution of chemical industrial parks in different provinces.

By 2018, there are 676 (petro-) chemical industrial parks: 57 national-level industrial parks, 351 provincial-level industrial parks and 224 prefectural-level industrial parks (Xinhua News Agency, 2019). These chemical industrial parks are mainly distributed in the provinces of Jiangsu, Shandong, Hubei, Henan and Inner Mongolia. These chemical industrial parks are mainly distributed in the provinces of Jiangsu, Shandong, and Hubei. Jiangsu is one of the richest provinces in China and has a developed industrial system that needs a lot of chemical products as raw materials. Besides, the Yangtze River flows through Hubei and Nanjing, providing convenient transportation for the development of the chemical industry. Most of the chemical companies in the two provinces distribute along the Yangtze River. Moreover, Hubei is situated in the middle reaches of the Yangtze River and the Hubei section of the Yangtze River is the longest in all provinces. The Shengli oilfield in Shandong is able to provide considerable raw materials for the petrochemical companies in the province. The coastline of the Shandong province also provides convenient maritime transportation for petrochemicals and chemicals.

4. Chemical accident analysis

4.1. An overview of China's chemical accidents in the period 2004–2018

This section provides an overview of China's chemical accidents from 2004 to 2018. Two official statistics from the MEM, including the China Work Safety Yearbooks (SAWS, 2004–2016) and the National Chemical Accident Analysis Report (2017–2018) (DSSMHC, 2018, 2019).

4.1.1. Accident trend analysis

In order to capture the overview of China's chemical accidents in recent 15 years, Fig. 4 depicts the number and fatalities (of chemical accidents) evolution over time from 2004 to 2018.

Fig. 4 is divided into three parts by dotted lines since the statistical method used by the State Administration of Work Safety changed twice in the 15 years. From 2004 to 2010, only fatal accidents related to hazardous materials were recorded by SAWS. The fatal accidents without hazardous materials were also collected from 2011 to 2015. From 2016, all accidents (with and without fatalities) in the chemical industries in China were collected. The first safety regulation specially for hazardous chemicals called "Regulation on the Safe Management of Hazardous Chemicals" was issued in 2002. From 2004 to 2010, the absolute number of accidents and fatalities decreased by 69.0% and 53.6% respectively. The number of accidents and fatalities decreased rapidly after 2006 due to the release of the "Safety Regulation on Construction Projects of Hazardous Chemicals". The decrease rates were 54.0% and 48.2% from 2011 to 2015 since the publication of the revised "Regulation on the Safe Management of Hazardous Chemicals"

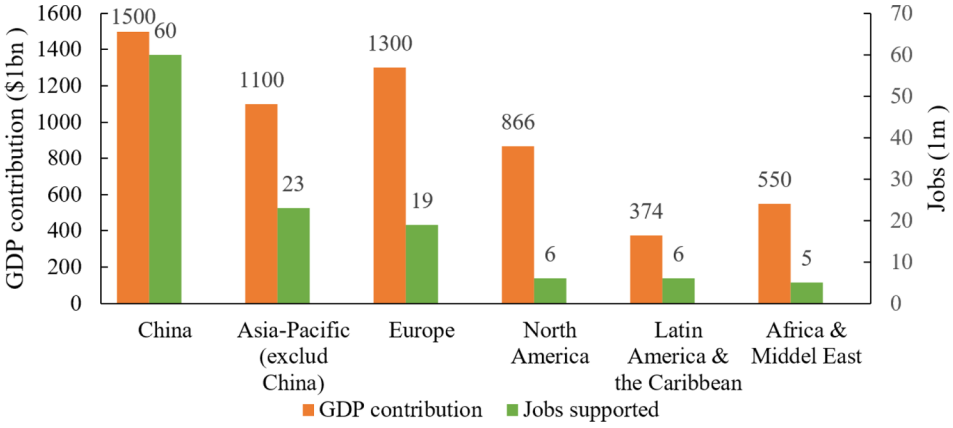

Fig. 2. The GDP contributions and jobs supported by chemical industries in different regions, adapted from Oxford Economics (2019).

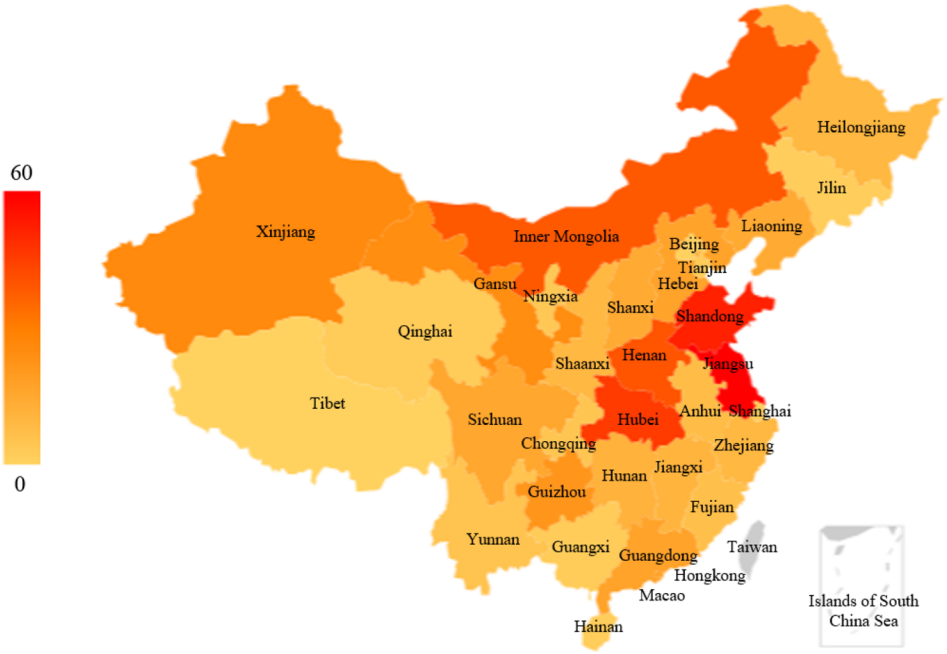

Fig. 3. The distribution of chemical industrial parks in China.

in 2011. The number of accidents in 2018 decreased by 22.1% compared to that in 2016 while the number of fatalities only decreased by 4.7%. The historical data demonstrate that the chemical industry in China are becoming safer. However, the decrease rate of fatalities was always lower than that of accidents, which indicates that the ratio of fatalities and accidents are increasing, as shown by the gray curve. For example, the ratio was 1.0 in 2016 while it was 1.3 in 2018 due to higher-level accidents. The increase in the average number of fatalities per accident demonstrates that the consequences of a single chemical accident in China are becoming more severe. This demonstration can also be verified by the major chemical accidents in recent years.

4.1.2. Accident level analysis

In this study, accidents are divided into four categories according to the Chinese regulation of "Accident report, investigation and handling regulations", as shown in Table 1.

As shown in Table 1, the classification is based on the fatalities, serious injuries, and direct economic losses caused by the accident. According to this classification, the fatalities caused by different kind of accidents from 2011 to 2018 are illustrated in Fig. 5. Most fatalities were caused by ordinary accidents and no tremendous accident occurred during the entire period (the official statistic data excluded the tremendous accident in Tianjin port in 2015). From 2011 to 2015, the fatalities caused by ordinary accidents decreased by 148 units (61.4%) and also decreased by 64 units (32.3%) from 2015 to 2018. However, larger accidents (level II, III and IV) increased over time. The ratio of fatalities caused by higher-level accidents increased from 15.4% to 40% in the last three years. It demonstrates that China should pay more attention to preventing accidents of level II, III and level IV which may result in catastrophic consequences.

4.1.3. Accident analysis by province

The great regional disparities in the development of China's chemical industry have been displayed in Fig. 3. As a result, the safety level of the chemical industry in China may also change in different provinces. Fig. 6 illustrates the distribution of accidents and fatalities in

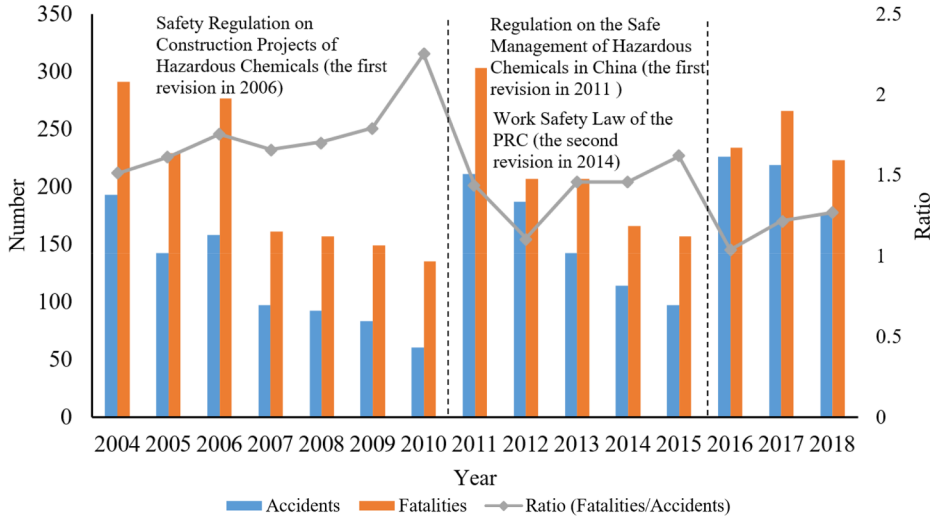

Fig. 4. Chemical accidents and fatalities evolution over time.

Table 1
Accident categories.

Level	Type	Description
I	Tremendous accident	An accident resulting in over 30 fatalities or over 100 serious injuries or over ¥100 million direct economic losses.
II	Large accident	An accident resulting in 10–30 fatalities or 50–100 serious injuries or ¥50-100 million direct economic losses.
III	Severe accident	An accident resulting in 3–10 fatalities or 10–50 serious injuries or ¥10–50 million direct economic losses.
IV	Ordinary accident	An accident resulting in below 3 fatalities or below 10 serious injuries or below ¥10 million direct economic losses.

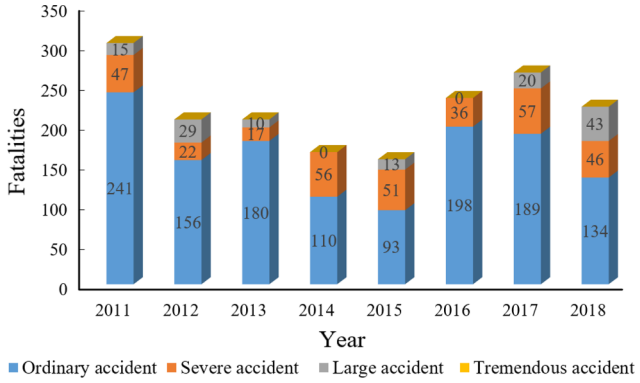

Fig. 5. The fatalities caused by different level of accidents from 2011 to 2018.

different provinces.

As shown in Fig. 6a, the number of accidents in the top 10 provinces concerns 61.0% of the total number of accidents. Shandong and Jiangsu have the most chemical accidents in absolute number (they also have the most chemical plants in China). The number of accidents in Jiangxi and Liaoning separately accounts for 7.1% and 6.1% of the total accidents although the chemical industries in the two provinces are not outstanding. Fig. 6b illustrates the fatality distribution by provinces in the last two years. Besides Jiangsu and Shandong, the number of fatalities in Hebei is also high because a large (level II) accident occurred in Zhangjiakou, Hebei, in 2018, resulting in 24 fatalities. This is also the case for Sichuan province in which a small number of accidents resulted in a high number of fatalities. From 2016 to 2018, level III or higher-level chemical accidents continuously occurred in Shandong and Sichuan. Guangdong is in top-3 with respect to the chemical industrial output value in China while only 1.3% of the total number of accidents occurred in Guangdong (ranking 27). Similarly, Shanghai only accounts for 1.0% of the total chemical accidents (ranking 29), much lower than its ranking in chemical industrial output values. The results indicate that the safety level of the chemical industry in less-developed areas (e.g., Liaoning, Jiangxi and Sichuan) is lower than that in developed areas (e.g., Guangdong and Shanghai). Consequently, more attention should be paid to the provinces with the large chemical industry and the provinces in less-developed areas.

4.1.4. Accident analysis by company scale

According to the regulation "Statistical classification of large-sized, medium-sized and small-sized enterprises" issued by the National Bureau of Statistics of China (NBSC), the industrial companies that have had accidents are divided into three categories: I (large-sized), II (middle-sized) and III (small-sized). The details of the classification is shown in Table 3.

To investigate the safety status of chemical companies in different sizes, chemical accidents in different sizes are analyzed, as shown in Fig. 7.

The number of accidents that occurred in large companies is less than that in small companies and in medium-sized companies probably since large companies may pay more attention to safety and they have larger financial means to devote to safety. Besides, the supervision and inspection of large companies are much easier than that of small companies. In China, the provinces of Jiangsu and Shandong have most chemical companies while the majority of the chemical companies are small-sized or medium-sized and located outside chemical industrial parks. This is one of the reasons why so many chemical accidents occurred in the two provinces. In order to prevent chemical accidents and protect the environment, Jiangsu and Shandong will close part of the companies, mainly small-sized and medium-sized companies. Tanking Jiangsu as an example, the number of chemical companies will be decreased to 1000 by the end of 2022, implicating that 80% of the chemical companies in Jiangsu province will be closed.

4.2. Cause-consequence analysis of Chinese chemical accidents

The collected chemical accidents are characterized by date, location, fatalities, injuries, accident levels, origins, hazardous substances, and causes. Table A in the appendix lists 170 chemical accidents used in this study. These accidents are characterized by level I, II, or III from 2004 to 2019 (level IV accidents are excluded).

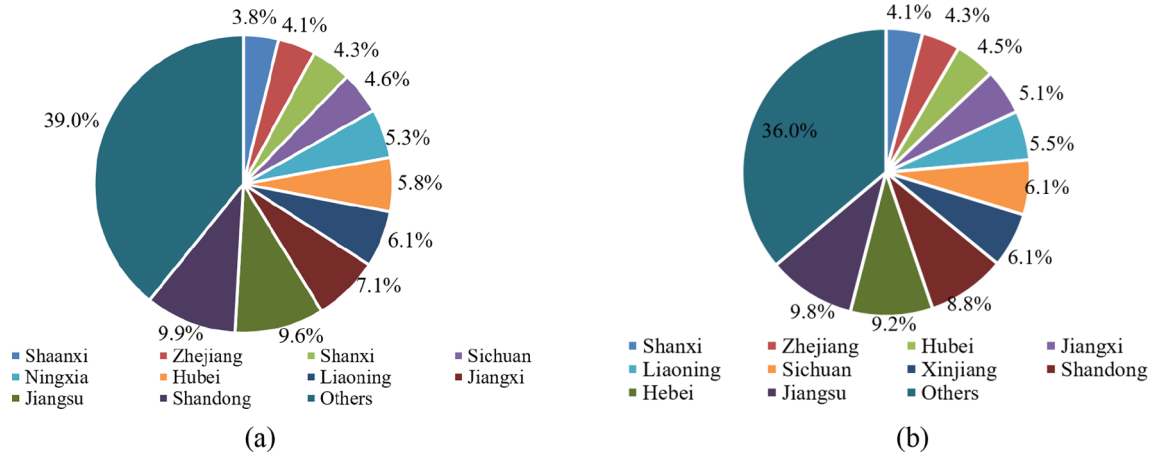

Fig. 6. The distribution of (a) accidents and (b) fatalities by province (top-10).

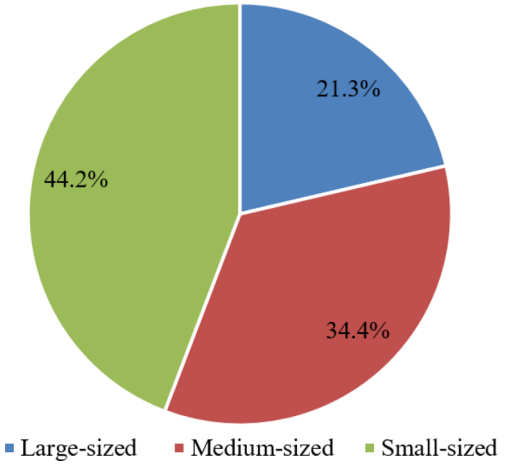

Fig. 7. The accident distribution by company scales.

Table 2
Statistical classification of large, medium and small industrial enterprises (NBSC, 2003).

Categories	Large-size	Middle-size	Small-size
The number of employees	2000	300–2000	< 300
Sale per year (¥ million)	300	30–300	< 30
Total property (¥ million)	400	40–400	< 40

4.2.1. Accident scenario analysis

At present, chemical accidents still frequently occur in China and result in many fatalities according to the above analysis. To get insight into chemical safety in China, a thorough cause-consequence analysis is conducted in this subsection. Table 2 lists the accident scenarios considered in the study.

Fig. 8 shows the scenario and enterprise-size distribution of these accidents. Among the 170 accidents, explosion is the most common scenario (56.2%), followed by toxic release (33.7%) and fire (21.3%). Domino effects were observed in 7.7% of these accidents and more than half of these accidents resulted in over ten fatalities. The most tremendous accident occurred on 12 August 2015 in Tianjin, resulting in 165 deaths and 8 people missing, 798 injuries, and huge property losses. Although asphyxia was only responsible for 5.9% of these accidents, it should not be ignored since multiple fatalities (one by one) are always present in the rescue process. Besides, 37 of the 170 accidents were related to multiple scenarios[3]. "Explosion to fire" is the most common sequence of domino accidents with respect to multiple scenarios. Moreover, these accidents mainly occurred in small-size enterprises, which demonstrates that the safety level of these companies needs to be improved and the safety supervision for these companies should be enhanced.

4.2.2. Accident origin analysis

The origins of accidents are divided into six categories: process areas (P), storage areas (SA), transfer (TR: loading and unloading), waste storage or disposal areas (WD), warehouse (WA), domestic or commercial premises (DC). Fig. 9 shows the origin of accidents.

Most of the accidents originated from process areas, followed by storage areas, and waste storage or disposal areas. As a result, process areas can be regarded as the most dangerous areas while the hazards of waste storage or disposal areas were always ignored by operators, resulting in casualties. Besides, 80% of accidents that occurred at storage areas were related to explosions and only one with a toxic release, indicating that preventing explosions is of great urgency.

4.2.3. Hazardous chemical analysis

More than seventy different hazardous chemicals were identified in the collected accidents. Hydrogen sulfide was responsible for most of these accidents, resulting in poisoning events. Next was carbon monoxide, followed by hydrogen, as shown in Fig. 10. Although nitrogen is not a hazardous substance, it is able to cause asphyxia due to a high concentration in a confined space. Compared with hydrogen sulfide and carbon monoxide, coal gas and petroleum vapor are prone to cause explosions rather than poisoning events.

4.2.4. Accident cause analysis

Seven types of causes (safety or security-related) and the cause instances adopted in this study are illustrated in Table 3.

The direct causes of chemical accidents are shown in Fig. 11. It is obvious that human errors were the main cause related to these accidents, likely due to bad safety culture and low safety awareness of the employees in many Chinese chemical plants. The problem may be more severe in some small or medium-sized chemical companies due to insufficient safety investments and with lacking safety supervision. Company leaders should pay more attention to building or improving the safety culture within a company via safety education, safety training, and communication, etc.

Human errors can be present at any stage of the lifecycle of a chemical facility. As a result, human errors may be classified into six categories. Fig. 12 illustrates the distribution of different types of human errors based on the accident data in this study.

As shown in Fig. 12, these accidents were mainly attributed to operating errors and maintenance errors which accounted for 62.2% of the total number of chemical accidents. Operating errors were mainly caused by operators within chemical companies while other types of human errors may be related to contractors. In that case, contractors also play an important role with respect to the safety of chemical plants. Hence, chemical plants should select contractors with good safety records and let them know the possible hazards at workplaces. In order to analyze the direct causes of chemical accidents in-depth, a fishbone diagram was used as shown in Fig. 13.

The fishbone diagram provides a qualitative approach for analyzing more detail the causes of chemical accidents in China. The operating errors were mainly caused by wrong procedures (violating procedure or regulations), clean operation and operation in confined spaces. Clean operation and other operations in a confined space without authorization and hazard identification were very likely to induce poisoning events or asphyxiation. It should be highlighted that most of the victims, in that case, were rescue workers who died one by one in the process of blind rescues (without protection). 22.9% of the total number of accidents related to blind rescues, also lead to accident escalation. The causes of wrong raw materials, loading and unloading errors and operational sparks indicate that employees' operational skills and safety knowledge in China's chemical industry need to be improved.

Both violating procedures (regulations) and entering confined spaces also exist in maintenance, responsible for more than half of the maintenance errors. Different from operational errors, maintenance errors may result in more severe consequences when they are related to contractors. The employees from contractors possibly begin working without knowing the equipment, processes and possible hazards in the workplace, resulting in accidents. The persons working on the site from contractors should know equipment and process information, possible hazards, and may be trained in order to ensure their safety. Welding is also a non-ignorable factor in maintenance since fire, sparks, or melting substances induced by welding may ignite flammable substances.

[3] Accidents related to multiple scenarios denote that more than one accident scenario (e.g., fire, explosion, toxic release, Asphyxia) is involved in the accidents, such as the accidents involving fire and explosion, explosion and toxic release as well as toxic release and asphyxia, etc.

Table 3
The chemical accident scenarios adopted in this study.

Scenario	Symbol	Description
Fire	F	An exothermic oxidation reaction caused by the ignition of flammable substances, resulting in the effect of heat radiation.
Explosion	E	A violent exothermic oxidation reaction caused by delayed ignition of flammable substances, resulting in overpressure; The confined explosion resulting from equipment overpressure.
Toxic release	T	Not-ignited release of toxic gas.
Asphyxia	A	Asphyxia due to the lack of oxygen.
Domino effects	D	An accident in which a primary unwanted event (fire or explosion) propagates to nearby equipment, causing a chain of unwanted events, resulting in the consequences more severe than the primary event.

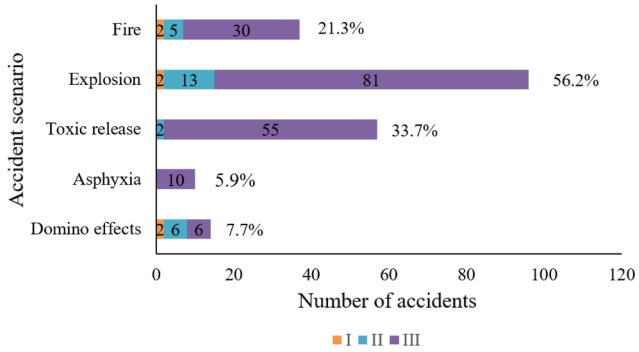

Fig. 8. The scenario distribution of chemical accidents in China (2004–2019).

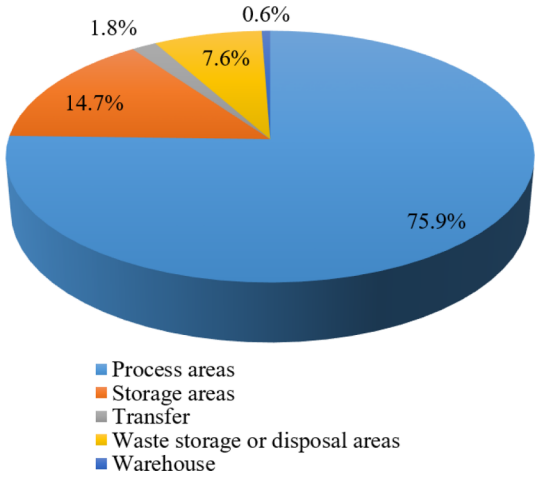

Fig. 9. The origin distribution of accidents.

However, several accidents caused by welding (without allowance) demonstrate that welders lack safety consciousness and supervision. Other human errors include design errors, inspection errors, and installation errors, etc.

Mechanical failure is also a critical cause, accounting for 20.0% of chemical accidents, including leaking pipes, valve failure, and the failure of other equipment. Besides, corrosion, ageing, and material cracking and overpressure may lead to the release of hazardous substances, resulting in major accidents. Violent reaction (e.g., confined explosion and runaway reaction) is also a common cause with respect to chemical accidents. In addition, Two accidents were related to natural hazards (extremely high temperature and extremely low temperature), resulting in 168 fatalities.

5. Analysis of Chinese legislation related to chemical safety

In 2001, China established the State Administration of Work Safety (SAWS) which is mainly responsible for the supervision of work safety

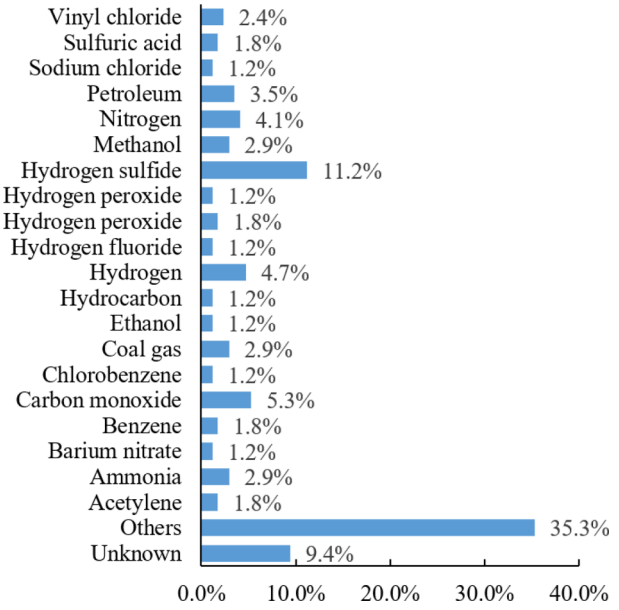

Fig. 10. The distribution of chemicals in collected accidents.

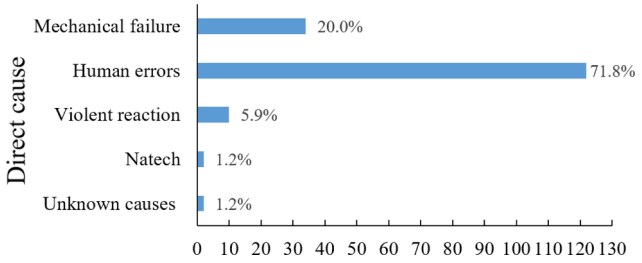

Fig. 11. Direct causes of the chemical accidents considered in this study.

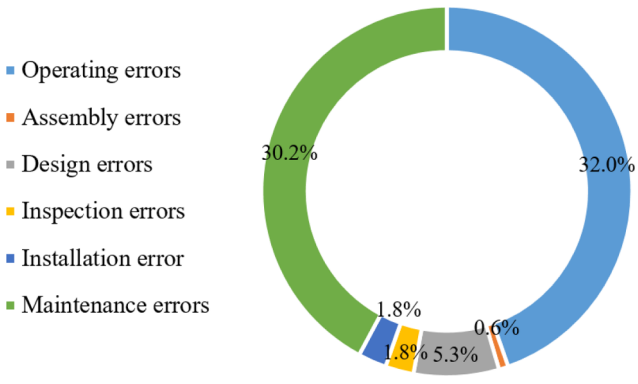

Fig. 12. The distribution of different types of human errors.

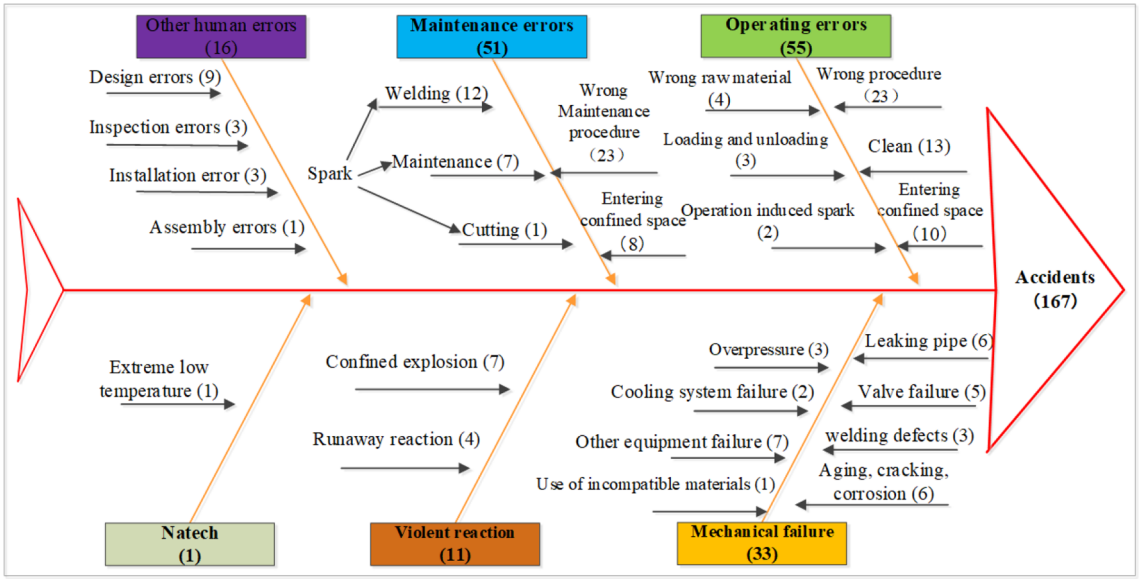

Fig. 13. Fishbone diagram for a cause analysis of chemical accidents in China from 2004 to 2019.

and coal mining safety. The third department of the SAWS is specially established for safety management and supervision of chemical industry, hazardous materials, medicines, and fireworks. In 2018, the SAWS was substituted by the Ministry of Emergency Management (MEM) and the Department of Safety Supervision and Management of Dangerous Chemicals was established for chemical safety management and supervision. This section will introduce important laws, regulations and guidelines related to chemical safety in China since 2011.

5.1. Chinese laws and regulations related to chemical safety

In order to deal with these accidents and improve the safety of chemical companies, China issued a series of laws, regulations, and standards. Table 4 lists the main laws, regulations, and standards related to chemical safety in China.

In 2002, the National People's Congress (NPC) Standing Committee released the important law "Work Safety Law of the PRC" to improve work safety in China (NPC Standing Committee, 2002). The law prescribed the safety requirements for enterprises, the rights, and obligations of practitioners, safety supervision, emergency response, and accident investigation, and the legal liability of different stakeholders. The safety management principle of "safety first, precaution crucial" was written into the law. Then the principle was revised as "safety first, prevention-oriented and comprehensive management" in 2014. Besides, The article of hazard identification and management was also established in the second revised version (NPC Standing Committee, 2009, 2014). The State Council of PRC issued the "Regulation on the Safe Management of Hazardous Chemicals in China" in 2002 for enhancing the safety management of hazardous chemicals. The regulation prescribed the requirements for the production, storage, use, sale, and transportation of hazardous chemicals as well as emergency rescue related to hazardous chemical accidents and legal liability (The State Council 2002). The regulation was further revised in 2011 and in 2013 (The State Council, 2013).

According to the "Work Safety Law of the PRC" and the "Regulation on the Safe Management of Hazardous Chemicals in China", the State Administration of Work Safety published the "Safety Regulation on Construction Projects of Hazardous Chemicals" in 2006 to improve the inherent safety of chemical facilities. In the regulation, safety assessments were required in the design stage and for completion of facilities, before operation (SAWS, 2006). The regulation was replaced by the "Regulation on Safety Operation Licenses for Hazardous Chemicals Enterprises" in which safety supervision is highlighted (SAWS, 2012).

Table 4
The accidental causes adopted in this study.

Causes	Symbol	Instances
Mechanical failure	MF	Corrosion, fatigue, weld failure, brittle failure, leaking seal
Human errors	H	Maintenance, operation, design, overfilling
Violent reaction	V	Runaway reaction, confined explosion
Natech	N	Lighting, earthquake, flood, extreme temperature
Sabotage	S	Terrorist attacks, crimes
Other causes	O	Causes that can not be classified into the previous categories
Unknown causes	U	Unknown causes

5.2. Standards and guidelines used in China for chemical industrial accidents

Besides these safety laws and regulations, the Chinese central government and local governments also released standards and guidelines to support safety management with respect to hazardous chemicals and the chemical industries. Table 5 lists the main national standards and Guidelines related to chemical safety.

In 1986, the General Administration of Quality Supervision (GAQS) issued the first national standard on the safety of hazardous chemicals "GB 6944-1986 Classification and Code of Dangerous Goods" (GAQS, 1986). Then the standard was revised twice in 2005 and 2012. According to the latest standard, hazardous chemicals are divided into nine categories: (i) explosive chemicals, (ii) gases, (iii) flammable liquids, (iv) flammable solids, spontaneous combustion chemicals, chemicals that can generate flammable gases when exposed to water, (v) oxidizing substances and organic peroxides, (vi) toxic and infectious chemicals, (vii) radioactive chemicals, (viii) corrosive chemicals and (ix) others (GAQS, 2012a). According to the classification, the national standard of "GB 12268-1990 List of Dangerous Goods" was issued in 1990 to improve safety management related to hazardous goods in transport, production, and storage and sale process. Hazardous chemicals (e.g., flammable, explosive, and toxic chemicals) are listed in the standard. The standard was improved in 2005, 2007, and 2012 (GAQS, 2012b).

In 1993, the national standard "GB 50183-1993 Fire Prevention Code for Crude Oil and Natural Gas Engineering Design" used in the

Table 5
The main national laws, regulations, and standards related to chemical safety in China.

Year	Laws or regulations	Organization
2002	Regulations on the Safe Management of Hazardous Chemicals in China	State Council of People's Republic of China (PRC)
2002	Work Safety Law of the PRC	National People's Congress (NPC) Standing Committee
2006	Safety Regulation on Construction Projects of Hazardous Chemicals	State Administration of Work Safety
2009	Work Safety Law of the PRC (the First Revision)	National People's Congress (NPC) Standing Committee
2011	Regulation on the Safe Management of Hazardous Chemicals in China (the First Revision)	State Council of PRC
2012	Regulation on Safety Operation Licenses for Hazardous Chemicals Enterprises	State Administration of Work Safety
2013	Regulations on the Safe Management of Hazardous Chemicals in China (the Second Revision)	State Council of PRC
2014	Work Safety Law of the PRC (the Second Revision)	National People's Congress (NPC) Standing Committee

design stage for preventing fire accidents was released (Ministry of Construction of PRC, 1993). The standard was revised in 2004 and 2015 (Ministry of Construction of PRC, 2015). The standard formulated the requirements for the layout of hazardous installations (e.g., the safety distance between hazardous installations), hazardous installations (e.g., tanks and process facilities), pipelines (e.g., the safety distance between pipelines and other infrastructures), and firefighting systems (e.g., fire Pumps and fire extinguisher), etc.

To prevent major accidents in chemical industries and other industries related to hazardous chemicals, China released the national standard "GB 18218-2000 Identification of Major Hazard Installation" (GAQS, 2000). The standard was replaced as "GB 18218-2009 Identification of major hazard installations for dangerous chemicals" in 2009 and was revised again in 2018 (GAQS, 2018). The standard provided a threshold value for each hazardous chemicals, then use the ratio of the mass of hazardous substances in the installation to the threshold quantity for determining the hazard levels. If the ratio is greater than 1, then the installation should be considered as a major hazardous installation.

In 2013, the State Administration of Work Safety of China released the "Guidelines for quantitative risk assessment of chemical enterprises". The guidelines introduce quantitative risk assessment (QRA) into the chemical industry in China, providing the basic requirements for a QRA in chemical enterprises. The adopted QRA methodology in the guidelines consists of eight steps: (a) preparation, (b) collection of data and information, (c) hazard identification, (d) analysis of failure frequency, (e) analysis of failure consequences, (f) risk calculation, (g) risk evaluation, (h) formulation of a risk assessment report. Although the guidelines were formulated in 2013, chemical enterprises have not been forced to conduct QRA in their chemical plants.

In order to standardize the safety management of chemical (hazardous chemicals) enterprises, guide and strengthen the safety supervision work of local governments, and better promote the implementation of the main responsibility of chemical enterprises, the State Administration of Work Safety issued the "Guidelines on safety Inspection Catalogue for Chemical (Hazardous Chemicals) Enterprises" (SAWS, 2015). Based on the "Work Safety Law of the PRC", 40 key inspection contents were formulated in the guidelines, including the inspection of safety certifications, the inspection of professional and safety knowledge of staffs, the inspection of safety education and training, and the inspection for safety measures, etc.

Most recently, after the Tianjiayi domino accident in Jiangsu, in 2019, the Ministry of Emergency Management (MEM) released two guidelines for hazardous chemical enterprises: "Guidelines on Safety Risk Identification and Management in Chemical Industrial Parks" and "Guidelines on hazard Identification and Management in Hazardous Chemicals Enterprises" (MEM, 2019a,b). The two guidelines were issued in order to improve the safety management level of chemical industrial parks and dangerous chemical enterprises. According to the first guideline, chemical industrial parks should periodically conduct risk assessments and propose protection measures to reduce the identified risk (the assessment cycle should be less than five years). The location of chemical industrial parks and the layout of hazardous installations within chemical industrial parks are highlighted in these guidelines. Moreover, it is the first time that domino effect assessment and management was formally required to be conducted in chemical industrial parks. In the second guideline, multiple hazard identifications and risk assessment methods are recommended in hazardous chemical enterprises, such as Safety Checklist (SCL), Hazard and Operability Study (HAZOP), and Risk Assessment Matrix. Besides, several safety checklists are provided for hazard identification in these enterprises.

5.3. Comparative analysis between China and Europe of prevention policies for major accidents

This subsection provides a comparative analysis of prevention policies regarding major accidents, comparing China with Europe. Table 6 illustrates a comparison of the released documents in China and Europe.

As shown in Table 6, the released documents in China are obviously issued later than those in Europe since the chemical industry developed at a start stage in China. In the light of the catastrophic accident in Seveso, Italy, in 1976, the Council of the European Union issued the so-called Seveso-Directive (Directive 82/501/EEC) in 1982 to prevent major accident hazards involving dangerous substances. The directive was revised and extended to Seveso-II (Directive 96/82/EC) in 1996. In that year, the National Occupational Health and Safety Commission of Australia also issued the National Standard "NOHSC: 1014(1996) Control of Major Hazard Facilities" for controlling major accidents in Australia. In view of the above documents in Europe and Australia, China released a national standard "GB 18218-2000 Identification of Major Hazard Installations" in 2000 to identify installations that may induce major accidents. Next, in 2002, the State Council of PRC legislated the "Regulation on the Safe Management of Hazardous Chemicals in China" to enhance safety management of hazardous chemicals.

There are obvious differences in these documents between China and Europe. The difference is obvious when it comes to managing domino effects in chemical industrial areas because chemical clusters appeared much later in China than in Europe ((Table 7)). Domino effect analysis and prevention are required in article 8 of Seveso-II (1996) while the Work Safety Committee of State Council of PRC started to pay attention to the domino effects in 2012 (Safety Committee of State Council of PRC, 2012) and the Ministry of Emergency Management of PRC just formally required chemical industrial parks to analyze and prevent domino effects in this year after the Tianjiayi domino accident (MEM, 2019b).

Besides, China issued the guidelines on QRA in 2013 while the guidelines in the Netherlands in Europe can be tracked to 1999 (purple book) (Uijt de Haag and Ale, 1999). As a result, chemical companies in China mainly conducted hazard identification according to the standard "GB 18,218 Identification of major hazard installations for dangerous chemicals" rather than risk assessment. The hazard identification method is based on a threshold value for each hazardous chemical, ignoring the uncertainty related to major accidents. While two thresholds (a low one and a high one) for each hazardous chemical were

Table 6
The main standards and guidelines related to chemical safety in China from 1990 to 2019.

Year	Standards or guidelines	Organization
1986	GB 6944-1986 Classification and Code of Dangerous Goods	General Administration of Quality Supervision, Inspection and Quarantine of PRC
1990	GB 12268-1990 List of Dangerous Goods	General Administration of Quality Supervision, Inspection and Quarantine of PRC
1993	GB 50183-1993 Fire Prevention Code for Crude Oil and Natural Gas Engineering Design	Ministry of Construction of PRC
2000	GB 18218-2000 Identification of Major Hazard Installations	General Administration of Quality Supervision, Inspection and Quarantine of PRC
2005	GB 12268-2005 List of Dangerous Goods	General Administration of Quality Supervision, Inspection and Quarantine of PRC
2009	GB 18218-2009 Identification of Major Hazard Installations for Dangerous Chemicals	General Administration of Quality Supervision, Inspection and Quarantine of PRC
2012	GB 6944-2012 Classification and Code of Dangerous Goods	General Administration of Quality Supervision, Inspection and Quarantine of PRC
2012	GB 12268-2012 List of Dangerous Goods	General Administration of Quality Supervision, Inspection and Quarantine of PRC
2012	Guidelines on Further Strengthening Safety Management in Chemical Industry Park	Work Safety Committee of State Council of PRC
2013	AQ/T 3046-2013 Guidelines for Quantitative Risk Assessment of Chemical Enterprises	State Administration of Work Safety
2015	GB 50183-2015 Code for Fire Protection Design of Petroleum and Natural Gas Engineering	Ministry of Housing and Urban-Rural Development of PRC
2015	Guidelines on Safety Inspection Catalogue for Chemical (Hazardous Chemicals) Enterprises	State Administration of Work Safety
2018	GB 18218-2018 Identification of major hazard installations for dangerous chemicals	General Administration of Quality Supervision, Inspection and Quarantine of PRC
2019	Guidelines on Safety Risk Identification and Management in Chemical Industrial Parks	Ministry of Emergency Management of PRC
2019	Guidelines on hazard Identification and Management in Hazardous Chemicals Enterprises	Ministry of Emergency Management of PRC

Table 7
A comparison of the released documents in China and Europe.

Aim	Europe	China
Classification, labeling and packaging of chemicals	1967, Council Directive 67/548/EEC and 1999, Directive 1999/45/EC and 2008, Regulation (EC) No 1272/2008.	GB 6944-1986 Classification and Code of Dangerous Goods; GB 6944-2012 Classification and Code of Dangerous Goods; GB 12268-1990 List of Dangerous Goods; GB 12268-2005 List of Dangerous Goods; GB 12268-2012 List of Dangerous Goods.
Control major accidents	1982, Directive 82/501/EEC (Seveso-I); (Amendments 1987, 1988); 1996, Council Directive 96/82/EC (Seveso-II); Amendment (2003); 2012, Directive 2012/18/EU (Seveso-III).	2000, GB 18218-2000 Identification of Major Hazard Installations; 2002, Regulation on the Safe Management of Hazardous Chemicals in China; 2009, GB 18218-2009 Identification of major hazard installations for dangerous chemicals; 2011, Regulation on the Safe Management of Hazardous Chemicals in China (The first revision); 2012, Guidelines on Further Strengthening Safety Management in Chemical Industry Park; 2018, GB 18218-2018 Identification of major hazard installations for dangerous chemicals.

adopted in Seveso-II (Swuste and Reniers, 2017). Fortunately, the Ministry of Emergency Management of PRC required all chemical industrial parks to conduct a risk assessment after the Tianjiayi domino accident (MEM, 2019b). In China, there is usually a department in each chemical industrial park called “Management Committee of Chemical Industrial park”. The committee set up by local governments is responsible for the administrative affairs, able to play a role in safety management and supervision for every chemical industrial park. But the role should be enhanced to truly improve the safety of chemical industrial parks.

Much earlier than the department of Safety Supervision and Management of Dangerous Chemicals in China, a similar department called the “Minerva portal of the Major Accident Hazards Bureau” or so-called “Major Accident Hazards Bureau” (MAHB) at the European Commission's Joint Research Centre (JRC) was established in 1996. The MAHB provides a collection of technical information and tools supporting the decision-making on major accident prevention and chemical accident risk reduction in the European Union. At the request of the European Commission's Directorate General for the Environment (DG ENV), the JRC developed a database (web platform) called “Seveso Plants Information Retrieval System” (SPIRS) to manage major hazard establishments. All the member states mandatorily report major hazard establishments to the European Commission's SPIRS database according to Seveso II Directive and Seveso III Directive. The collected information in the SPIRS provides an overview of the number, spatial distribution and type of major hazard sites. By the application of Geographical Information Systems (GIS), SPIRS can map spatial components of the establishments and preparation of a variety of thematic maps. Besides, there is also a web platform called eMARS (Major Accident Reporting System) for reporting chemical accidents and providing the general public with access to accident information in order to reduce chemical accident risks. Based on eMARS, a suite of Accident Information and Data Analysis (AIDA) tools were provided by MAHB. The JRC also provides a software tool called “Accident Damage Analysis Module” (ADAM) to assess physical effects and associated damages of an industrial accident resulting from an unintended release of a hazardous substance (MAHB, 2017). However, there is a lack of these web platforms and tools in china for improving chemical safety.

6. Discussion

In order to promote the sustainable development of the chemical industry in China, this study investigated the chemical industry, chemical accidents, and chemical safety policies in China. This section, therefore, aims to provide a thorough discussion on chemical safety in China to answer the research questions posed in the introduction, finding out the possible safety problems in China’s chemical industry.

6.1. Possible causes of a large number of major accidents occur in China

6.1.1. The large scale of the chemical industry in China derived by economic benefits

China has more than 20,000 chemical companies, playing a leading role in the chemical industry and creating 40% of the global output with respect to chemical industrial activities. The expected number of chemical accidents in China is thus higher than in other countries given an identical probability of accidents in each company. It took only decades for China's chemical industry to reach its present scale. High-speed growth brought huge economic benefits yet it also comes with some negative effects, such as un-safety and environmental problems. Although the principle of "safety first" has been in the Work Safety Law of the PRC since 2002, safety issues seem to have been ignored compared to the huge economic benefits in this particular industrial sector.

6.1.2. Low-level safety knowledge and insufficient hazard information

The accident investigation in this study shows that 72.2% of chemical accidents in China were caused by human errors. It indicates that the practitioners in the chemical industry lack safety- and professional knowledge. Most of the practitioners in China's chemical industry only have low-level education and are not aware of possible accident scenarios, always resulting in an underestimation of possible safety risks in workplaces. Besides, chemical companies may not fully inform workers from contractor companies about the possible risk in the workplace and they may also lack supervision for these workers, leading to maintenance errors, inspection errors, installation errors, etc.

6.1.3. The improvement of chemical safety didn't match the rapid development of the chemical industry in China

In recent decades, a series of laws, regulations, guidelines, and standards have been issued for improving China's safety strategy so as to prevent chemical accidents. However, differences in governmental safety policies between China and other countries such as in Europe still exist. The improvement speed of safety strategy does not match the high-development of the chemical industry in China. Regulations and guidelines are usually issued after one or more severe accidents, resulting in the delay of safety improvements. For instance, the regulation for preventing domino effects was only officially issued in 2019 after the Tianjiayi disaster. China only adopted the hazard identification method used in the European Seveso-II legislation while it ignored the article for the prevention of domino effects at that time.

6.1.4. Inadequate supervision and track for the implementation of safety measures

The performance of these safety laws, regulations, guidelines and standards depends amongst others on safety supervision. Many chemical accidents occur after the hazards had been identified, indicating that safety supervision needs to be enhanced in chemical plants in China. In order to get economic benefits, companies always reject to stop production even when safety departments ask them to close down for improving safety. For example, the Tianjiayi chemical company was criticized by the State Administration of Work Safety in February 2018 since 13 hazards in the chemical plant didn't meet the requirements. However, the domino accident in the Tianjiayi chemical company occurred in 2019 due to lax supervision and blindly pursuing economic benefits.

6.1.5. Too much attention on technical safety and neglection of human-related issues

According to Amyotte et al. (2016), significant contributions to the evolution of process safety can be divided into six phases: technical safety improvements, human error/human factors, management focus on HSE, safety management systems, safety culture, knowledge management/communication safety. In view of all the above observation and research results, China's safety improvements mainly focused on technical safety (e.g., safety equipment, fireproof materials), neglecting other important tasks for improving safety in China, such as human errors which are responsible for most of the chemical accidents in China.

6.2. Possible causes of a large number of casualties caused by major accidents in China

6.2.1. Large population density and too many employees

Compared with major accidents in developed countries, China's major accidents usually result in more casualties. According to the chemical industry analysis in this study, China's chemical industry not only contributes a lot to China's GDP but also provides a considerable number of jobs. The average number of workers in a chemical company in China is far more than that in Europe or in North America. As a result, a major accident in a Chinese company may result in more casualties than the same accident in Europe due to more workers being present at the workplace.

6.2.2. Lack of emergency knowledge and lower-level emergency management

Accident investigation demonstrates that unsuitable rescues are the main causes resulting in the escalation of toxic release/asphyxia accidents. The most common scenario is that one worker gets poisoned and other workers aim to resue the poisoned worker only also to get positioned one by one, leading to an accident consequence escalation. The emergency response strategies used in these chemical companies are not able to reduce the possible consequences of accidents and the practitioners regretfully lack the capabilities of emergency rescues. As a result, an unsuitable rescue not only can not reduce the consequences of the accident, but it may also lead to accident escalation, resulting in more casualties.

6.2.3. The increase in the proportion of large accidents

The average number of casualties in a chemical accident slightly increased in recent years due to the increase in the ratio of larger accidents to ordinary accidents. It indicates that the safety strategy in China doesn't focus enough on the prevention of large accidents and possible domino effects induced by industrial clusters.

6.3. Possible future pathways of chemical safety in China

The subsection provides several recommendations for improving chemical safety and sustainability in China and other countries with similar characteristics.

6.3.1. Safety economics-based decision-making on safety strategies

Safety investments in a chemical company not only are part of risk management but also have a great impact on the effectiveness of a company's prevention policy as well as the company's profitability in the long term. The avoided losses caused by safety investments can be regarded as a hypothetical "benefit", facilitating the sustainable development of chemical companies. Different from safety regulations, laws and guidelines, the application of safety economics such as cost-benefit analysis (CBA) is expected to encourage the decision-maker in chemical companies to consciously pay more attention to the long-term benefits caused by safety investments rather than short-term economic benefits obtained by sacrificing safety.

6.3.2. Safety education and training

The scarcity of safety knowledge and safety consciousness is a root cause of so many chemical accidents caused by human errors. Many operators in the chemical industry only have low education. As a result, safety courses related to risk-thinking, safety and risks related to hazardous substances should be popularized not only in higher education institutions but also in lower education institutions such as vocational

schools. Enhancing safety training is another way to improve safety knowledge and safety consciousness. Safety training needs to be provided to both operators in chemical companies and workers from contractor companies.

6.3.3. Safety culture

Improving safety culture in chemical companies is a long-term mechanism for preventing chemical accidents. A good safety culture can be enhanced by changing safety attitude and behavior, management commitment to safety, management concerns for the workforce, training and seminars, continuous organizational learning, continuous monitoring, etc. (Vecchio-Sadus and Griffiths, 2004; Choudhry et al., 2007; Meyer and Reniers, 2016). Chemical companies should continuously invest more in safety culture rather than just safety technologies.

6.3.4. Emergency response

Many accident escalations highlighted the lack of emergency response capability in China's chemical companies. Companies should help employees to obtain emergency response knowledge and build self-protection awareness in emergency rescues. Professional emergency management teams and a detailed emergency management plan should be developed in chemical companies to reduce the consequences of major accidents, avoiding accident escalation.

6.3.5. Prevention of large accidents and domino effects

Large accidents such as domino effects may be regarded as low-frequency and high-impact events. However, the risk of domino effects can not be neglected concerning so many chemical industrial parks in China and the severe consequences. China should pay more attention to the prevention of major accidents and domino effects via legislation, land-use planning, inherent design, risk assessment and management on low-frequency and high-impact events.

6.3.6. Improving regulations and enhancing safety supervision

Although China has issued a series of regulations on hazard identification related to hazardous substances and chemical safety, legislation on risk assessment and management in chemical industrial areas should be enhanced. Safety supervision is a guarantee for the performance of safety regulations. Safety departments should supervise the safety improvement process of chemical companies rather than only use punishment after identifying illegal hazards. Besides, safety inspection should be more specific, such as inspection cycles, inspection contents, and the inspection after safety rectification.

6.3.7. Quantitative risk assessment and dynamic risk assessment

Quantitative risk assessment (QRA) is a systematic risk analysis approach to quantifying the risks associated with the operation of an engineering process (Uijt de Haag and Ale, 1999). Although China has released guidelines on QRA, it hasn't been legislated. The main risk analysis approach used in China still is hazard identification based on thresholds. QRA should be popularized in China's chemical industry. Besides, China is still in urbanization, process technology, equipment used in the chemical industry and the layout outside chemical companies is changing rapidly over time. The risk assessment cycle should be shorter than that in developed countries. Besides, other advanced risk analysis tools such as dynamic risk assessment may also be used and promoted in chemical companies.

6.3.8. Improving automation management and reduce employees in hazardous areas

Compared with developed countries, China's chemical companies have more staff, which increases the likelihood that employees are exposed to different kinds of hazards. Improving automation and reducing the number of employees in hazardous areas may reduce fatalities once an accident occurs in chemical industrial areas.

6.3.9. Enhancing the role of the management Committee of chemical industrial park in safety management and supervision

The "Management Committee of Chemical Industrial Park" is mainly responsible for the setting and management of various infrastructures and public facilities in a chemical industrial park. But the committee's role in safety management and supervision should be enhanced to reduce the workload of the local department for emergency management and improve the safety of single companies as well as the safety of the entire chemical industrial park. For example, the committee may promote cooperation prevention of external domino effects (that is, accidents occurring in one company that can escalate to other companies, resulting in a severe disaster of the entire chemical industrial park).

6.3.10. Developing information management platforms and technical tools for chemical accident prevention

In Europe, the Minerva Portal of the Major Accident Hazards Bureau provides web platforms for managing major hazard establishments and major accidents. Besides, accident analysis tools such as AIDA and ADAM are also provided for users. In China, similar web platforms should be installed and improved to better manage chemical companies and chemical accidents. Technical tools for accident and risk analysis may also be provided to help chemical companies to reduce major accident risks.

7. Conclusions

In the present study, we developed a systematic methodology to investigate the current status, problems and future needs of chemical safety and sustainability in China. The methodology consists of four steps: an overview of China's chemical industry, investigation of chemical accidents in China, analysis of Chinese safety policy, and discussion of problems and needs. Chemical companies always expect to pursue short-term economic benefits and ignore work safety, resulting in fatalities and large economic losses, and discouraging sustainable development. As a result, safety economics such as cost-benefit analysis (CBA) is recommended in this study to encourage the decision-maker in chemical companies to consciously pay more attention to the long-term benefits caused by safety investments. Accident cause categorization shows that human errors are the main cause of chemical accidents in China, and the lack of emergency response capabilities always results in accident escalation. China needs to pay more attention to human errors, safety culture, and safety management rather than only focus on technological safety. Self-protection awareness and emergency response capabilities need to be strengthened to reduce the consequences of the primary scenario.

Besides, the average number of casualties in a single accident slightly increases in recent years due to major accidents. The prevention of major accidents such as domino effects could and should, therefore, be enhanced. The threshold-based hazard identification approach was legislated and has been the main risk assessment method in China's chemical industry, which may not be enough for adequate chemical safety management. More advanced risk analysis methods such as quantitative risk assessment and dynamic risk assessment need to be popularized further. Moreover, the role of the Management Committee of Chemical Industrial Park in safety management should be enhanced to promote cooperation safety investment and improve the safety of the entire chemical industrial park. Using a comparative analysis between China and Europe, we also conclude that China needs to develop information management platforms for chemical plant management, major accident analysis, and technical tools to help companies analyze and manage major accident risks. These recommendations on chemical safety in China can contribute to the long-term sustainable development of the chemical industry.

References

Amyotte, P.R., Berger, S., Edwards, D.W., Gupta, J.P., Hendershot, D.C., Khan, F.I., Mannan, M.S., Willey, R.J., 2016. Why major accidents are still occurring. Curr. Opin. Chem. Eng. 14, 1–8.

Chen, C., Reniers, G., Khakzad, N., 2019a. Cost-benefit management of intentional domino effects in chemical industrial areas. Process Saf. Environ. Prot. 134, 392–405.

Reliab. Eng. Syst. Saf. 191, 106470. https://doi.org/10.1016/j.ress.2019.04.023.

Chen, C., Reniers, G., Khakzad, N., 2020. A thorough classification and discussion of approaches for modeling and managing domino effects in the process industries. Saf. Sci.

Chen, C., Reniers, G., Zhang, L., 2018. An innovative methodology for quickly modeling the spatial-temporal evolution of domino accidents triggered by fire. J. Loss Prev. Process Ind. 54, 312–324.

Choudhry, R.M., Fang, D., Mohamed, S., 2007. The nature of safety culture: a survey of the state-of-the-art. Saf. Sci. 45, 993–1012.

Cozzani, V., Gubinelli, G., Antonioni, G., Spadoni, G., Zanelli, S., 2005. The assessment of risk caused by domino effect in quantitative area risk analysis. J. Hazard. Mater. 127, 14–30.

DSSMHC, 2018. Analysis report 2017 for chemical and hazardous chemicals accidents in China. Retrieved from: http://121.22.39.66/qhdfile/webfile/03/2018/152567265459bd9c7ecd08084e5589c1.pdf. (Accessed July 14, 2019).

DSSMHC, 2019. Analysis report 2018 for chemical and hazardous chemicals accidents in China. Retrieved from: http://www.zhejianghuaan.com/uploadfiles/2019/02/2018%E5%B9%B4%E5%8C%96%E5%B7%A5%E5%92%8C%E5%8D%B1%E5%8C%96%E5%93%81%E4%BA%8B%E6%95%85%E5%88%86%E6%9E%90%E6%8A%A5%E5%91%8A.pdf. (Accessed July 14, 2019).

Duan, W., Chen, G., Ye, Q., Chen, Q., 2011. The situation of hazardous chemical accidents in China between 2000 and 2006. J. Hazard. Mater. 186, 1489–1494.

EMIS, 2019. China's chemical industry 2018/2022. Retrieved from. (Accessed August 30, 2019).

GAQS, 1986. GB 6944-1986 Classification and Code of Dangerous Goods.

GAQS, 2000. GB 18218-2000 Identification of Major Hazard Installation.

GAQS, 2012a. GB 6944-2012 Classification and Code of Dangerous Goods.

GAQS, 2012b. GB 12268-1990 List of Dangerous Goods.

GAQS, 2018. GB 18218-2018 Identification of major hazard installations for dangerous chemicals.

Hong, S., Jie, Y., Li, X., Liu, N., 2019. China's chemical industry: new strategies for a new era. Retrieved from: https://www.mckinsey.com/industries/chemicals/our-insights/chinas-chemical-industry-new-strategies-for-a-new-era. (Accessed July 13, 2019).

Kiss, A.A., 2019. Rethinking Energy Use for a Sustainable Chemical Industry. CHEMICAL ENGINEERING 76.

Liu, T., Zhong, M., Xing, J., 2005. Industrial accidents: challenges for China's economic and social development. Saf. Sci. 43, 503–522.

MAHB, 2017. The Minerva Portal of the Major Accident Hazards Bureau. Retrieved from: https://ec.europa.eu/jrc/en. (Accessed January 30, 2020).

MEM, 2019a. Guidelines on hazard Identification and Management in Hazardous Chemicals Enterprises.

MEM, 2019b. Guidelines on Safety Risk Identification and Management in Chemical Industrial Parks.

Meyer, T., Reniers, G., 2016. Engineering Risk Management. Walter de Gruyter GmbH & Co KG, Berlin.

Ministry of Construction of PRC, 1993. GB 50183-1993 Fire prevention code for crude oil and natural gas engineering design.

Ministry of Construction of PRC, 2015. GB 50183-2015 Code for fire protection design of petroleum and natural gas engineering.

NBSC, 2003. Statistical classification of large-sized, medium-sized and small-sized enterprises.

NPC Standing Committee, 2002. Work Safety Law of the PRC, In: Committee, N.S. (Ed.).

NPC Standing Committee, 2009. Work Safety Law of the PRC (The first revised), In: Committee, N.S. (Ed.).

NPC Standing Committee, 2014. Work Safety Law of the PRC (The second revised), In: Committee, N.S. (Ed.).

Oxford Economics, 2019. The Global Chemical Industry: Catalyzing Growth and Addressing Our World's Sustainability Challenges. Retrieved from. (Accessed August 30, 2019).

Reniers, G., Cozzani, V., 2013. Domino Effects in the Process Industries, Modeling, Prevention and Managing. Elsevier, Amsterdam, The Netherlands.

SAWS, 2004-2016. China Work Safety Yearbook 2004-2016. Retrieved from: http://www.xinhuanet.com/energy/2019-05/24/c_1124535295.htm. (Accessed August 29, 2019).

SAWS, 2006. Safety Regulation on Construction Projects of Hazardous Chemicals, In: Safety, T.S.A.o.W. (Ed.).

SAWS, 2012. Regulation on Safety Operation Licenses for Hazardous Chemicals Enterprises, In: Safety, T.S.A.o.W. (Ed.).

SAWS, 2015. Guidelines on Safety Inspection Catalogue for Chemical (Hazardous Chemicals) Enterprises. Retrieved from: http://www.waizi.org.cn/law/19308.html. (Accessed August 29, 2019).

Sun, K., Yang, H., 2011. Statistical analysis of dangerous chemical accidents in China. Fire Technol. 48, 331–341.

Swuste, P., Reniers, G., 2017. Seveso inspections in the European low countries history, implementation, and effectiveness of the European Seveso directives in Belgium and the Netherlands. J. Loss Prev. Process Ind. 49, 68–77.

The State Council 2002. Regulation on the Safe Management of Hazardous Chemicals in China, In: PRC, T.S.C.o. (Ed.).

The State Council, 2013. Regulation on the Safe Management of Hazardous Chemicals in China, In: PRC, T.S.C.o. (Ed.).

The State Council, 2019. The Investigation report on "March 21"tremendous accidentexplosion accident of Jiangsu Xiangshui Tianjiayi Chemical Co., Ltd. Retrieved from: https://www.mem.gov.cn/gk/sgcc/tbzdsgdcbg/2019tbzdsgcc/201911/P020191115565111829069.pdf. (Accessed January 30, 2020).

Uijt de Haag, Ale, 1999. Guidelines for quantitative risk assessment. Committee for the Prevention of Disasters, The Hague (NL).

Vecchio-Sadus, A.M., Griffiths, S., 2004. Marketing strategies for enhancing safety culture. Saf. Sci. 42, 601–619.

Wang, B., Wu, C., Kang, L., Reniers, G., Huang, L., 2018a. Work safety in China's Thirteenth Five-Year plan period (2016–2020): current status, new challenges and future tasks. Saf. Sci. 104, 164–178.

Wang, B., Wu, C., Reniers, G., Huang, L., Kang, L., Zhang, L., 2018b. The future of hazardous chemical safety in China: opportunities, problems, challenges and tasks. Sci Total Environ 643, 1–11.

Work Safety Committee of State Council of PRC, 2012. Guidelines on Further Strengthening Safety Management in Chemical Industry Park, In: Work Safety Committee of State Council of PRC (Ed.).

Xinhua News Agency, 2019. The central and local governments have enhanced supervision and then the chemical industry in China may change. Retrieved from: http://www.xinhuanet.com/energy/2019-05/24/c_1124535295.htm. (Accessed July 13, 2019).

Yang, J., Li, F., Zhou, J., Zhang, L., Huang, L., Bi, J., 2010. A survey on hazardous materials accidents during road transport in China from 2000 to 2008. J. Hazard. Mater. 184, 647–653.

Yang, Y., Chen, G., Chen, P., 2018. The probability prediction method of domino effect triggered by lightning in chemical tank farm. Process Saf. Environ. Prot. 116, 106–114.

Yang, Y., Chen, G., Reniers, G., 2019. Vulnerability assessment of atmospheric storage tanks to floods based on logistic regression. Reliab. Eng. Syst. Saf. 106721.

Zeng, T., Chen, G., Yang, Y., Chen, P., Reniers, G., 2019. Developing an advanced dynamic risk analysis method for fire-related domino effects. Process Saf. Environ. Prot.

Zhang, H., Zheng, X., 2012. Characteristics of hazardous chemical accidents in China: a statistical investigation. J. Loss Prev. Process Ind. 25, 686–693.

Zhao, J., Suikkanen, J., Wood, M., 2014. Lessons learned for process safety management in China. J. Loss Prev. Process Ind. 29, 170–176.