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Why do major chemical accidents still happen in China: Analysis from a process safety management perspective

Mingqi Bai [a], Meng Qi [a], Chi-Min Shu [b], Genserik Reniers [c], Faisal Khan [d,*], Chao Chen [e], Yi Liu [a,*]

[a] College of Chemistry and Chemical Engineering, China University of Petroleum (East China), Qingdao 266580, China
[b] Department of Safety, Health, and Environmental Engineering, National Yunlin University of Science and Technology, Yunlin 64002, Taiwan, ROC
[c] Safety and Security Science, Faculty of Technology, Policy and Management, Delft University of Technology, Delft 2629Hz, the Netherlands
[d] Mary Kay O'Connor Process Safety Center, Texas A&M University, College Station, TX 77843-3122, USA
[e] School of Petroleum Engineering, Southwest Petroleum University, Chengdu 610500, China

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ABSTRACT

As an important consideration in the chemical industry, chemical process safety has received notable attention in China. However, catastrophic chemical accidents still occur. To better understand why accidents continue to occur, this paper presented a diagnostic analysis of 14 major chemical accidents in China from 2012 to 2022 based on VOSviewer software. The authors analysed the correlation between the accident causation and their relationship with the safety management elements. The study observed that inferior process safety culture, intentional violation (rule-breaking) of procedure, inadequate safety training, and illegal operations were the most frequent causes of accidents. These causes highlighted the prominent gaps in PSM in China in the process safety culture, compliance with standards, the conduct of operations, process safety competency, and training & performance assurance. The results based on co-occurrence analysis indicated a strong correlation between these gaps in PSM. Enterprises should pay attention to collaborative management among them. These deficiencies in the enterprise's PSM system showed that the essential defects in China's chemical industry are a poor safety culture, inadequate accident investigation, inadequate training, and a lack of chemical safety personnel. The study recommended that the chemical industry establish superior process safety culture and competency for all personnel, monitor leading and lagging process safety indicators, apply inherent safety, and practice advanced safety management concepts. We hope that the findings can provide China's perspectives and strengths for global chemical safety.

1. Introduction

The chemical industry is one of the pillar industries of the nation's economy, which is closely integrated with other industries, including agriculture, pharmaceuticals, metallurgy, construction, energy, national defence, and the environment (Ahmad et al., 2021; Liaw, 2019; Zhang et al., 2020b). The chemical industry has become a pivotal sector as a result of China's rapid economic expansion (Chen and Reniers, 2020). According to Fig. 1, China's sales of chemicals have increased year by year from 2010 to 2020, and its share in the global market has grown steadily. However, most chemicals are inherently hazardous, such as inflammable, explosive, and toxic. Besides, there are more unsafe factors in the production process of the chemical industry, such as high-temperature, high-pressure machinery, aerial works, and confined space works, which will pose high risks (Ahmad et al., 2019; Mohd Shariff et al., 2016). In the event of an accident, it may cause a large number of casualties and property damage (Castillo-Landero et al., 2022; Wang et al., 2016). Actually, serious accidents occurred frequently as the chemical industry expanded. On August 12, 2015, an explosion at a hazardous materials facility in Tianjin port caused 165 deaths, 798 injuries, and direct economic losses of 0.98 billion U.S. dollars (Yang et al., 2020a). In 2019, an explosion at Tianjiayi Chemical Co., Ltd. killed 78 people, injured 76, and resulted in a direct economic loss of about 0.28 billion U.S. dollars (Yang et al., 2020b). These accidents have posed a salient challenge to the chemical industry. Chemical safety has become more vital and prominent in China due to the country's large and even expanding chemical industry.

Chemical safety has always been a critical concern of the Chinese

* Corresponding authors.
E-mail addresses: fikhan@tamu.edu (F. Khan), liuyi@upc.edu.cn (Y. Liu).

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government and academia (Anuradha et al., 2020; Casciano et al., 2019; Janošovský et al., 2022; Ortiz-Espinoza et al., 2021; Roy et al., 2016; Song et al., 2021; Syeda et al., 2022; Zhang and Wang, 2022; Zhu et al., 2022). The Chinese government is currently looking for a solution to achieve adequate chemical process safety. On September 02, 2010, the Work Safety Committee of the China State Council (WSCCSC, 2022) promulgated the "Measures for the Supervision of the Major Accidents' Investigation", which requires the Safety Committee of the State Council to supervise the investigation of major accidents and disclose the investigation findings to the public. Since 2010, more laws and regulations related to safe production have been adopted in China (Wang et al., 2018a). The Chinese government has prioritised safety production since 2012 and has organised numerous seminars to provide the essential principles for safe production. The historical evolution of major and particularly serious accidents and regulatory milestones in China from 2012 to 2022 is displayed in Fig. 2. China's "14th Five-Year Plan" for hazardous chemicals emphasised strengthening safe production monitoring and early warning, as well as supervision and law enforcement (Ministry of Emergency Management of China, 2022).

With the in-depth research of scholars and the stringent requirements of the government, chemical safety in China has been promoted continuously in recent years. As shown in Table 1, the number of chemical accidents and fatalities in China has been decreasing year by year from 2019 to 2021. The number of serious accidents fell below ten for the first time in 2021 (Ministry of Emergency Management of China, 2021, 2021). Numerous scholars have conducted a statistical and in-depth analysis of accidents in China, aiming to identify their root causes and suggest plans for chemical safety in China. Yang et al. (2020) pointed out that the hot topics of process safety research in China include risk assessment models, optimisation of dangerous chemicals transportation, numerical simulation of accident consequences, safety management, the domino effect in the chemical industry parks, process fault diagnosis, and reliability analysis. Based upon the chemical accidents in China from 2004 to 2019, Chen et al. (2020) summarised the possible causes of a large number of prominent accidents in China, including inadequate safety knowledge, insufficient information on hazards, the excessive size of China's chemical industry and the prompt growth of the industry, the poor supervision of the implementation of safety measures, and neglect of the human errors. Wang et al. (2018b) counted the Chinese laws, standards, and safety regulatory agencies for hazardous chemicals. They analysed the chemical accidents by year, company type, geographic region, accident type, and life cycle. Although the statistical data on chemical accidents are not precisely the same based upon previous literature, the above researchers come to the same conclusion that the total number of chemical production accidents in China fluctuates but shows a slow downward trend with the increase in chemical process safety concerns (Liu, 2017). Although academics have conducted deep research to advance chemical safety, there is still one issue that has to be addressed: why do major chemical accidents still occur in China in the last decade? Amyotte et al. (2016) and Silva (2016) presented similar questions several years ago: Why are major accidents still occurring?

Table 2 lists the categorisation of accidents in chemical industries in China (State Council of PRC, 2007). As illustrated in Fig. 3, the authors counted the consequences of all major and particularly serious accidents in the past decade reported by the Ministry of Emergency Management of China. Major chemical accidents occurred almost every year from 2012 to 2019, resulting in substantial property losses and casualties. The continued occurrence of major accidents prompts us to ponder these questions that were we doing the wrong analysis, or were companies incapable of improving chemical safety? Actually, recognising the deficiencies in company safety management and understanding the underlying reasons for employee or company errors is crucial.

Based upon various statistical methods, accident statistical analysis can investigate the frequency of accidents and their distribution characteristics to better understand the causes of accidents, control potential risks, and avoid accidents (Li et al., 2022; Xie et al., 2022; Xu et al., 2022; Zhang et al., 2020a). After the accident investigation, the causes of accidents are often diverse, and some of them may recur in subsequent accidents, suggesting a strong correlation between some of these frequently recurring causes. The causes of the accidents indicate a vulnerability in some process safety management (PSM) elements during their implementation in the company. Some significant defects of a PSM element might reflect the safety concepts deficiencies of company's leaders or employees, and these defects probably exist in other PSM elements. Thus, there should be a relationship between the different PSM loopholes.

When a safety management vulnerability is identified, it should be carefully investigated whether other highly correlated vulnerabilities exist at the same time. Furthermore, we intend to acquire insight into the PSM vulnerabilities in China's chemical sector by exploiting PSM gaps in numerous firms to explain why big chemical mishaps continue to occur in China in recent years. Therefore, the VOSviewer software was applied to compare and analyse the causes in the investigation reports of major and particularly serious accidents in China from 2012 to 2022 to explore the relationship between accident causes and safety management deficiencies in China's chemical industry. The novelty of this paper lied in analysing accidents from the perspective of PSM and exploring correlations of PSM vulnerabilities. This paper aimed to determine why accidents continue to occur and methods to avoid major accidents and investigate the inadequacy of safety management in the chemical companies of China. Furthermore, this paper investigated the recommendations to ameliorate safety performance of the chemical industry in China and provided a Chinese perspective and strengths for global

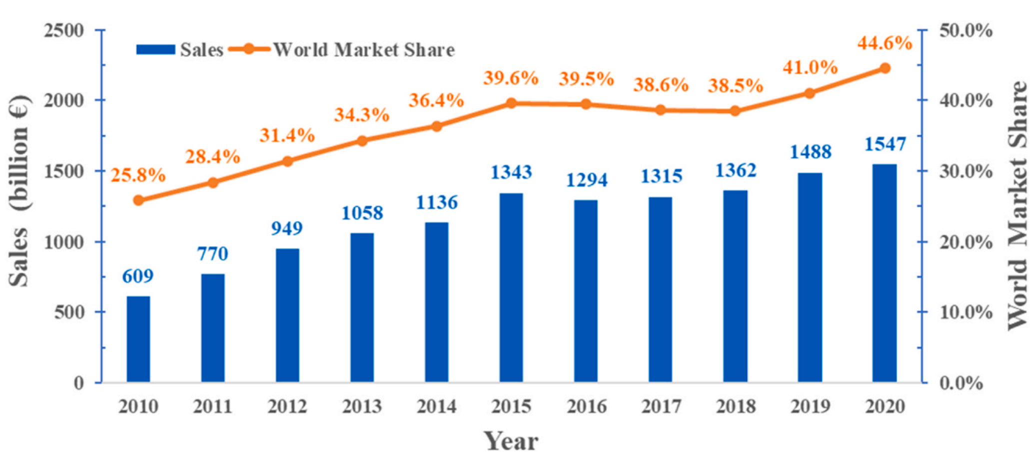

Fig. 1. Chemicals sales in China from 2010 to 2020 (CEFIC, 2022, 2022).

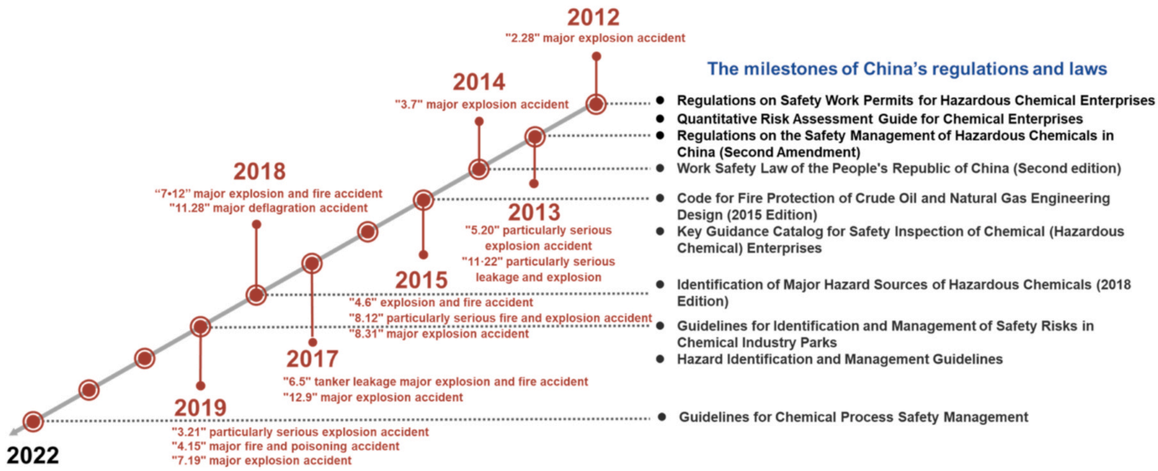

Fig. 2. The historical evolution of major and particularly serious accidents in China linked to regulation milestones from 2012 to 2022 (red: accidents; black: regulations).

Table 1
Statistics on chemical accidents and death tolls in China from 2019 to 2021.

Year	Accident number	Deaths
2019	164	274
2020	144	178
2021	122	150

Table 2
Categorisation of accidents in chemical industries in China.

Categorisation	Deaths	Serious injuries	Direct economic losses (million Yuan)
Ordinary accident	< 3	< 10	< 10
Serious accident	3–10	10–50	10–50
Major accident	10–30	50–100	50–100
Particularly serious accident	> 30	> 100	> 100

chemical safety.

2. Methodology

The VOSviewer software was created to generate and visualise bibliometric graphs, which are often used to probe the correlation of publications among journals, authors, institutions, nations, and research themes. The fundamental principle of the VOSviewer software is co-occurrence clustering algorithm, which states that the appearance of two things simultaneously indicates their relationship (Wei et al., 2022). The similarity s_{ij} between two nodes i and j is related to the number of times they appear simultaneously, as shown in Eq. (1):

$$s_{ij} = \frac{c_{ij}}{w_i w_j} \tag{1}$$

where c_{ij} represents the frequency that node i and node j appear simultaneously; w_i and w_j express the frequency that nodes i and j appear, respectively.

The VOSviewer software creates knowledge map clustering diagrams using Eqs. (2) and (3) to make the results more understandable:

$$s_{ij} = \frac{c_{ij}}{w_i w_j} V(x_1, .., x_n) = \sum_{i<j} s_{ij} \| x_i - x_j \|^2 \tag{2}$$

$$\frac{2}{n(n-1)} \sum_{i<j} \| x_i - x_j \| = 1 \tag{3}$$

where $x_{i \text{ or } j}$ annotates the position of node i or j; $\| x_i - x_j \|$ stands for Euclidean distance between nodes i and j; n represents the overall number of nodes in the network.

This principle can be fully exploited to analyse causal correlations among multiple accidents. Multiple co-occurrences of some accident

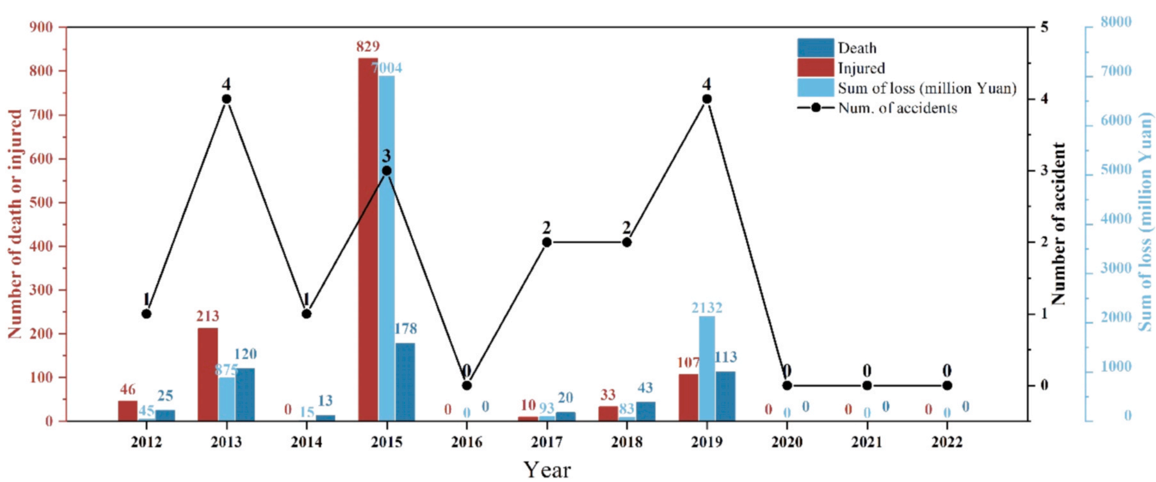

Fig. 3. Major and particularly serious chemical accidents happened in China from 2012 to 2022.

cause or PSM vulnerabilities show their correlation. As a result, by generating input files for the VOSviewer software, this study applied the software's correlation calculation method to determine the correlation between each accident cause and the correlation between each PSM element (Khan et al., 2016; Sattari et al., 2021). The detailed procedures of the correlation analysis are shown in Fig. 4.

(1) Collection of the accident investigation reports
Since 2010, the Chinese government commenced to officially report major and particularly major accident information, leading to the establishment of a comprehensive database for such accidents (Ministry of Emergency Management of China, 2023). The investigation reports for these accidents can be publicly available. Based upon official reports from the Chinese government, there have been a total of 15 chemical accidents since 2010. However, because of the invalidation of the report on one chemical accident in 2011 by the Chinese government, which is no longer considered as an administrative reference, this paper analysed the remaining 14 reports of major and particularly major accident incidents. The details of these accidents were sourced from official reports issued by the Chinese government's Emergency Management Department to ensure their reliability. These reports have been made available for download on the official website of the Chinese government and the sources for these reports have been included in the Supplementary material.
(2) Extraction and classification of accident information
The causes of each accident were extracted from the accident report. To be recognised by the VOSviewer software, the same accident causes that may be expressed in multiple ways require to be re-described as the same phrase. Therefore, we established an analysis team including two university professors, three Ph.D. students who major in chemical safety engineering, one safety officer from a chemical company, and one safety expert from an industrial safety research institute. The analysis team brainstormed a re-description of each cause in the accident reports by using brief phrases or sentences. To point out the safety management gaps for each accident in a chemical plant, accident causes were assigned according to the CCPS 20 PSM elements. The analysis team discussed which PSM element is responsible for each accident's cause in the accident company, thereby identifying the PSM vulnerability.
(3) Correlation analysis of accident causes and PSM elements

The configuration of the input file was completed by downloading and revising a sample of the source input file of VOSviewer software. The document title, keywords, and authors' data were replaced with the accident name, causes, and PSM elements. Using the VOSviewer software, the correlation analysis of accident causes and safety management gaps was completed by the correlation analysis of the keywords and the authors, respectively. All files were added to the Supplementary material.

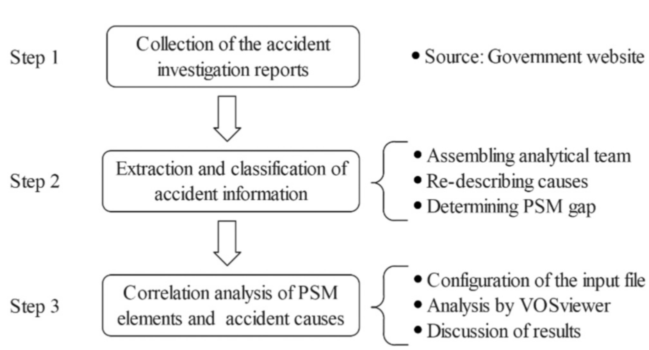

Fig. 4. Flow chart for the cause correlation analysis method by three steps.

3. Results and discussion

3.1. Cause analysis

Fig. 5 exhibits the relationship between the causes of major and particularly serious accidents in China from 2012 to 2022, and the details of all causes were added in the Supplementary material. The reasons with a higher frequency of occurrence will be classified into three categories and discussed in detail to demonstrate the primary issues of China's chemical industry. First, an inferior process safety culture contributes the most to 14 accidents. Safety culture is often closely linked to the implementation of other PSM elements. The chemical plant with inferior process safety culture has the following characteristics: (1) numerous violations exist in the plant, (2) the companies acquiesced to intentional violations of process safety standards or procedures, (3) the company lacks awareness of hazards and the associated consequences, (4) the company lacks sufficient safety experts and is unable to follow expert's opinions, and (5) the companies lack clear authorisation and requirements for safety responsibilities. The second most frequent cause of accidents is rule-breaking operations, insufficient safety training, and illegal operation, which happened in more than a dozen cases. These three causes suggest that, even if correct and safe operations have been recommended in the chemical industry, workers in the plants where these accidents occurred either did not know the correct operation or intentionally operated unsafely for convenience. Third, illegal production, illegal construction, unclear safety responsibility, inadequate safety personnel or departments, insufficient safety measures, insufficient management of safety information, and insufficient operating procedures occurred in half of the accidents. Some of these reasons demonstrate that plants do not prioritise safety, such as illegal production, illegal construction, unclear safety responsibility, and inadequate safety personnel or departments. These plants try to put economic interests ahead of safety production. Insufficient management of safety information and insufficient operating procedures would prevent employees from taking appropriate and timely action. Insufficient safety measures show that the company fails to forestall accidents in emergencies.

3.2. Cause correlation analysis

If some causes appear concurrently in multiple incidents, it indicates that they may be closely correlated. The cause of the accident might reflect the safety concepts deficiencies of company's leaders or employees, and these defects probably exist in other causes of the accidents. For example, if a company often fails to conduct timely equipment inspections and maintenance, it may display inadequacy in handling equipment failures during emergencies. Understanding the correlation between different factors will greatly assist the company in identifying risks comprehensively.

In the clustering algorithm of the VOSviewer software, items with the same colour belong to the same cluster, representing a strong correlation. According to the blue cluster in Fig. 5, illegal construction, unqualified assessment of third-party, and insufficient operating procedures may occur simultaneously in facilities with a poor safety culture. The red cluster suggests a close connection between inadequate safety personnel or departments, unclear safety responsibility, insufficient technical training, inadequate professional knowledge of the operator, overdue inspection and maintenance of equipment, inadequate emergency response capability, and legal violations of cooperative companies. The yellow cluster indicates that illegal production is closely related to unqualified personnel, inadequate emergency drill, and no emergency plan. The green cluster belongs to the rule-breaking operation, illegal operations, flawed risk assessment, and insufficient management of change systems. Insufficient safety training, insufficient management of safety information, and insufficient safety measure belong to the purple cluster. The finding reminds us that when a

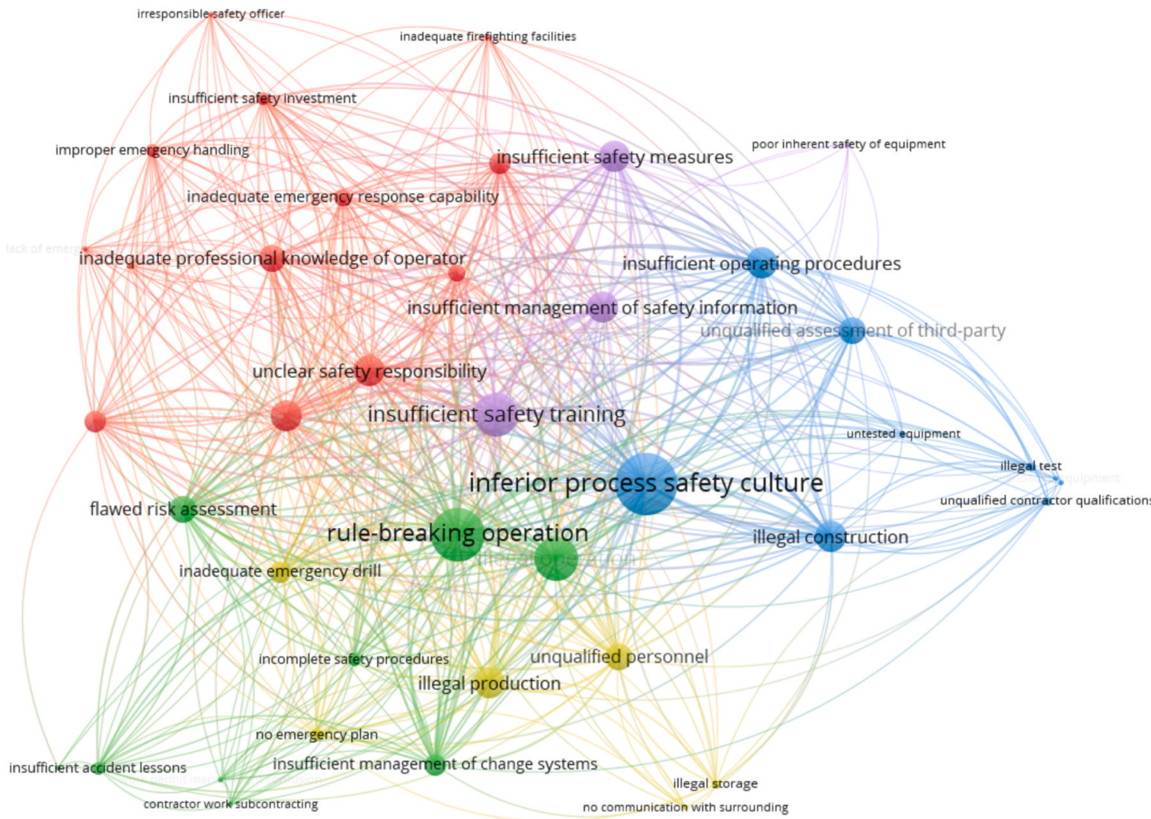

Fig. 5. Mapping of major accident causations (the clusters of red, blue, yellow, green, and purple represent different sets of strongly correlated reasons).

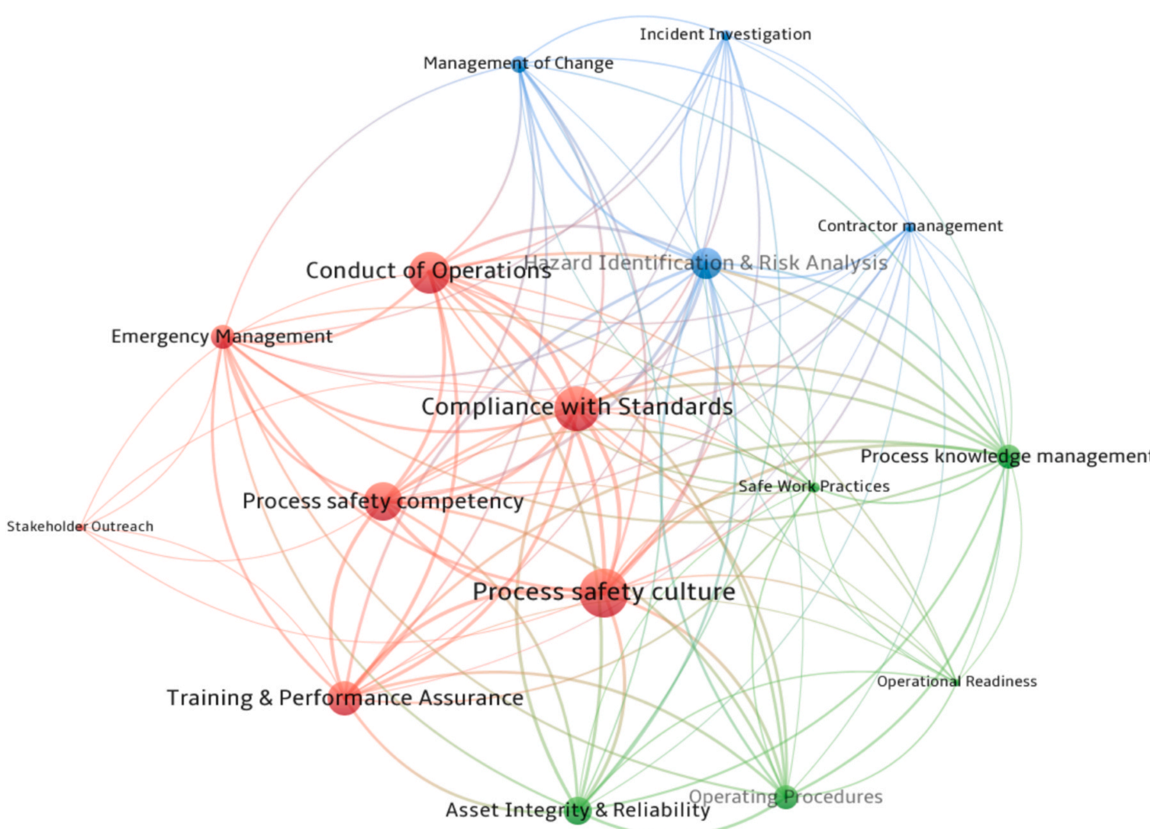

Fig. 6. The frequency and correlation of PSM elements in 14 accidents.

company discovers the problems mentioned above, it should also check for any other highly relevant causes, even though we cannot explain the direct relationship of problems in the same cluster.

3.3. Process safety management gap analysis

The PSM is widely used in the chemical industry. We applied statistical methods to illustrate the gaps in China's chemical safety management by matching the accident causes with the associated PSM elements.

The frequency and correlation between the different elements are portrayed in Fig. 6. The largest gaps, which appeared more than 10 times in 14 occurrences, were in the areas of process safety culture, compliance with standards, conduct of operations, and process safety competency, training & performance assurance. The loophole in the process safety culture element is mostly demonstrated by non-compliance with safety responsibility. The gap in compliance with standards is caused by the fact that all accidents involve illegal behaviours, such as illegal production, illegal operation, illegal storage, illegal construction, and legal violations of cooperative companies. Illegal behaviours refer to actions that violate national laws. The vulnerability of conduct of operations lies in the rule-breaking operation of employees. The gaps in the process safety competency include unclear safety responsibility, inadequate safety personnel or departments, unqualified personnel, inadequate professional knowledge of the operator, insufficient safety measures, inadequate emergency response capability, insufficient safety investment, and irresponsible safety officers. The loophole in training & performance assurance lies in inadequate safety and technical training.

Table 3 showcases the relationships among the PSM elements, and the classification results indicate that the companies should focus on the collaborative management of each cluster in safety management. As indicated by cluster 1, if a plant's process safety culture is substandard, it may have problems managing elements, such as standards compliance, conduct of operations, process safety competency, training & performance assurance, emergency management, and stakeholder outreach. As shown by cluster 2, when a plant needs to enhance integrity & reliability of its assets, it should also pay much attention to process knowledge management, operating procedures, safe work practices, and operational readiness. As denoted by cluster 3, there should be better communication between those responsible for hazard identification & risk analysis, management of change, contractor management, and incident investigation elements, as these elements are more closely related. It is crucial to note that Table 3 does not include the components of workforce involvement, measurement and indicators, auditing and management review, and continuous improvement because these causes of the accident are not expressed in all investigation reports.

3.4. Deficiencies in chemical safety in China

We reviewed the detailed investigation report in light of the above results and found the following deficiencies regarding chemical safety management in China.

Table 3
Correlation between PSM elements.

Cluster	PSM elements
1	Process safety culture, compliance with standards, conduct of operations, process safety competency, training & performance assurance, emergency management, and stakeholder outreach
2	Asset integrity & reliability, process knowledge management, operating procedures, safe work practices, and operational readiness
3	Hazard identification & risk analysis, management of change, contractor management, and incident investigation

(1) *Poor process safety culture*

The main gaps in China's chemical process safety management, as shown in Fig. 6, are the elements of process safety culture and compliance with standards. The investigation team accurately outlined the safety regulations and laws those companies had broken in each report. The companies in 14 accidents were certainly aware of the requirements of these widely known rules and regulations, but they violated them to increase their financial gains. Furthermore, they refused rectification and deceived supervisors, produced and operated without authorisation after they were reprimanded and ordered to rectify. As Hendershot (Hopkins, 2005) said, the issue with chemical companies today is not that we do not know what to do; rather, we do not always follow through on what we already know and should do. These wrong behaviours are typically attributed to the company's poor process safety culture. The existence of a poor safety culture can be attributed to leaders who have overlooked safety issues or prioritised other matters. Leaders who do not prioritise the development of a safety culture and understanding of hazards may lead to noncompliance and other deficiencies being viewed as normal for the sake of convenience. Furthermore, if the leadership does not recognise the importance of safety, they will not attract expertise to help them improve the situation, thereby forfeiting the opportunity to combine academic knowledge and research results from the university with industrial practices. The process safety culture is the root cause of the deficiencies in the PSM system in the "2–4″ model theory of the accident cause analysis (Huang et al., 2019; Qiao et al., 2019). Essentially, a poor safety culture will result in either an inadequately developed or even nonexistent process safety management system. As a result, the current focus for enhancing chemical safety in China is to establish a robust process safety culture.

(2) *Inadequate management of accidents and incidents*

The rule-breaking operations in 12 of the 14 accidents indicated a major vulnerability in the PSM elements of the conduct of operations. The investigation report of each incident showed the rules that employees broke and erroneous operations, but these contents are insufficient to improve the company's PSM. We need more information to support our investigation into why employees violated the rules rather than focusing on the fact that employees violated the rules. As Trevor Kletz (Crawley, 2016) said, people have stated that most accidents are caused by human error. It is true in some ways but not particularly useful, which is similar to arguing that falls happen due to gravity. An employee's violation may be due to his lack of knowledge of the correct procedure, which indicates a lack of training. This phenomenon is most likely to happen in companies with an impoverished process safety culture, where even leaders blame the operators' errors for their incompetence. Another significant reason for rule-breaking operations is that employees are aware of the correct procedures but refuse to follow them due to their flukes or laziness. To fundamentally alter this phenomenon, companies need to cultivate a positive process safety cultural atmosphere. Therefore, more detailed information, such as the motivations behind the rule-breaking operations, would help us better understand the accident's in-depth causes to assist in strengthening PSM in China. Furthermore, other companies can learn more from the accidents and ameliorate their safety management.

The quantity and quality of accident investigations are also an area of concern for China's chemical safety. Ordinary accidents and near misses are as vital as major and particularly serious accidents. However, the sharing of incident information is a prominent gap in China's chemical safety. Unfortunately, numerous companies view accidents as humiliating, so they try to hide the accident or cover up accident information. However, a high-quality accident investigation report can serve as a useful reminder and important lesson-learning for other companies experiencing similar problems. The authors tried to analyse more accidents, but we failed to acquire more accurate results because of the lack of complete accident information and the challenge of acquiring accident investigation reports. Mannan and Waldram (2014) advocated that open-access accident databases are as crucial as engineering and safety management systems upgrades. Therefore, companies need to carry out in-depth accident investigations and establish an open-access platform for sharing accident data to enhance the safety of China's chemical industry. The detailed recommendations regarding open-access accident databases are discussed in Section 4.3.

(3) *Shortcomings of the training and lack of chemical safety talents*

Fig. 6 shows that process safety competency and training & performance assurance are insufficient among the PSM elements in China's chemical industry. The vulnerabilities in process safety competency include unclear safety responsibility, inadequate safety personnel or departments, incompatibility in personnel qualifications, inadequate safety personnel or departments, unqualified personnel, inadequate professional knowledge of the operator, insufficient safety measures, inadequate emergency response capability, insufficient safety investment, and irresponsible safety officer. In particular, there were inadequate safety personnel or departments, unqualified personnel, or inadequate professional knowledge of operators in 10 of the 14 accidents. Undeniably, an inferior process safety culture noticeably impacts these reasons. For example, plants with a poor process safety culture would hire unqualified personnel to alleviate labour costs.

On the one hand, this phenomenon demonstrates that companies need to develop a sound safety culture. On the other hand, it also reflects a lack of talent in chemical safety. In contrast to the annual demand of about 30,000 chemical safety professionals in China, our previous research revealed that less than 3000 graduates with a background in chemical process safety education each year, resulting in a severe shortage of chemical process safety talents (Motalifu et al., 2022). In light of this status quo, companies might not be able to hire enough new employees with expertise in chemical safety. Second, companies lack qualified employees to train their permanent staff and contractors, which might also be a contributing factor to the lack of training & performance assurance.

Professional knowledge plays a major role in chemical safety. Most major accidents in the chemical industry occur because the necessary knowledge or competencies are not acquired at the right time and place (Perrin et al., 2018). Human intervention is typically utilised to avert accidents when a chemical process malfunctions. Human knowledge is essential when taking action to avoid or minimise the consequences of an accident. Lacking the necessary expertise, operators may misinterpret process variables, leading to incorrect diagnoses and actions. Undesired events could happen if operators lack the technical understanding required for the process (Silva, 2016). Particularly, the complexity of the system increases the potential for human error. Therefore, strengthening chemical safety talent education is a crucial strategy for addressing the talent gap.

4. Recommendations to improve safety performance

We make the following recommendation to improve process safety performance in chemical industries in China based upon the analysis.

4.1. *Create a sound process safety culture*

The inevitability of safety management implementation's drawback is that managers cannot continuously monitor each employee's compliance. Workers occasionally disregard safety norms and regulations to save time and effort. If they can do so without causing an accident, they will have the bravery to repeat or even intensify this risky activity. As mentioned earlier, process safety culture is the root cause of deficiencies in PSM systems. Thus, a process safety culture is essential to mitigate the inescapable drawback of safety technology and management. A sound process safety culture plays a vital part in other PSM elements, so other PSM elements will also improve with the safety culture. A superior process safety culture usually requires companies to strengthen the following efforts.

(1) Clear process safety culture goals

Chemical companies must first set process safety culture goals that require to be shared with the public and develop a work plan to achieve these goals. The safety culture to be achieved should be clearly described in the safety culture implementation plan. The company should ensure that there are no priorities that can compete with safety. One of the major reasons so many accidents occur is that companies choose production profits over safety when they are faced with the choice between the two options. Meanwhile, companies must be prepared to withstand notable changes and accept high investments when addressing some safety issues. Because there are no quick and easy solutions to some safety problems, major actions are required, which would include organisational adjustments, the replacement of key personnel, large investments in devices, and so on.

(2) Safety leadership

Many of the available works focused on safety culture and climate, consistently supporting the climate-leadership relationship (Zohar, 2010, 2008). Often, all departments and personnel strive to provide quality content that is valued by company leaders. In an immaculate company safety culture, the company's key leaders must realise the importance of safe production and practice safe behaviour through their actions. In addition, they need to encourage employees to engage in safe behaviours actively. Managers at all levels should spend sufficient time to involve safety practices as these are the locations where safety goals are achieved, and safety issues are identified.

(3) Adequate safety resources and authority

Developing a sound process safety culture requires more than just eye-catching safety slogans, it also requires investment, human resources, and time to address safety issues. Companies with a great safety culture recognise the true value of safety and view safety investments as quality ones that deliver a superior return rather than as expensive expenses. Furthermore, a safety management system should have a distinct division of work and responsibilities. Importantly, for safety employees to perform well in their roles, they must be given the resources and authority to identify and resolve safety issues.

(4) Safety work with full participation

Doing a sound job of safety requires everyone's joint efforts. Everyone plays an effective role in a safe work and safety culture. Effective ways to address safety issues include communication, analysis, and discussion. Regular plant-wide communication on safety issues is necessary because the internal safety communication process can enhance all employees' in-depth understanding of safety issues and convert safety knowledge into employees' safety capabilities. Some topics should be discussed, such as the degree of involvement in safety work, whether employees are receptive to requirements and activities concerning safety, and whether they are willing to report safety concerns to their supervisors. The company's safety activities will be exceptionally successful if employee participation is close to 100%. Employees should be encouraged, praised, and rewarded rather than blamed or punished for raising safety issues. Companies should also continue to motivate employees to engage in sound safety behaviour through rewards. In addition, managers at all levels should address any safety issues brought to their attention by staff expeditiously and effectively.

One of the requirements for hiring staff by companies should be proactive safety awareness. All staff members should possess the necessary safety expertise and operational skills within an excellent safety culture. To better carry out their duties, everyone needs to be aware of their safety obligations and actively receive safety training. Employees that do not follow with the company's safety principles ought to be fired or even discharged.

(5) Actively identify problems

The cost of relying on accidents to advance safety management is unacceptable. Companies require to identify existing risks and proactively develop controls, rather than exposing problems through accidents. According to Heinrich's law, as the number of minor incidents rises, so will the number of serious accidents (Marshall et al., 2018). Companies should implement an accurate, detailed, and high-standard injury reporting system. The truth of any accident and incident should not be allowed to be covered up.

4.2. Cultivation of chemical safety personnel

Chemical safety talents need to be cultivated due to the enormous talent gap in this field and the value of professional expertise. Talent education is a systematic project which includes training students majoring in chemical safety and plant staff. Government educational institutions must support universities, and company leadership must encourage staff training.

In our previous research (Motalifu et al., 2022), we emphasised the need for more universities to establish a chemical process safety research track in the safety engineering program and to establish a chemical safety engineering program. Chemical safety talents should develop comprehensive abilities, particularly process knowledge, safety knowledge, technological knowledge, and management abilities, to be competent in any field, such as process design and operation, scientific research, or safety management. Every course should incorporate a positive safety culture. For instance, safety knowledge is embedded in courses like chemical reaction engineering, and chemical process design, to help students continuously enhance their safety awareness by learning about the disastrous consequence of chemical accidents.

There are plenty of effective approaches to enhance chemical safety education, including international cooperation, lectures by specialists in chemical safety, and tours of chemical facilities. Faculty should focus on guiding students' ability to independent learning through various teaching methods, such as mobile classrooms and course practice. Internship in the chemical process industry can better understand chemical safety knowledge and the actual safety management work (Gajek et al., 2022; Mkpat et al., 2018; Perrin et al., 2018; Qian et al., 2023; Swuste et al., 2021). Meanwhile, this is also an effective way to evaluate the effectiveness of education. The government should encourage chemical companies, safety associations, and safety consulting companies to offer internship opportunities for students.

The assessment of educational quality is an area that requires close attention (Gajek et al., 2022; Mkpat et al., 2018; Perrin et al., 2018; Qian et al., 2023). The objectives of education are not only limited to imparting knowledge of safety to students but also to cultivating their safety awareness, such as determining whether they will prioritise safety issues in their future work efforts, especially when experiencing high levels of work pressure. Once they possess superior safety awareness, they will proactively identify risks and seek safety knowledge and assistance from safety experts when encountering safety issues. Therefore, in addition to assessing safety knowledge, evaluating student safety awareness is equally crucial. A questionnaire survey conducted six months after the completion of the course would be an exemplary method (Herink et al., 2022; Swuste et al., 2021).

A capable faculty team is a crucial element of efficient chemical safety education. With so few educators who are knowledgeable about safety and chemical engineering, there is an urgent need for professional chemical safety faculty in China. As a full-time or part-time college professor, the plant engineer is a great way to address the shortage of faculty for chemical safety courses. Attention should be paid to strengthening engineers' understanding of the teaching process to ensure adequate teaching quality. Faculty should also be encouraged to take temporary positions in chemical companies or cooperate in scientific research to enhance their engineering practice ability.

4.3. Accident root cause mining and immaculate accident database

Since rule-breaking operations frequently occur in accidents, it is extremely important to dig deeper into the causes of employee violations. The Management Oversight and Risk Tree (MORT) model is highly recommended for conducting root cause analysis (Ferjencik and Kuracina, 2008). This model utilises a tree diagram to uncover the underlying causes of accidents or incidents and can be aptly referred to as the genesis of root cause analysis (Santos-Reyes et al., 2010, 2009). The Noordwijk Risk Initiative Foundation has devised a readily accessible MORT manual to aid investigators in its implementation (NRI, 2002). When utilising MORT to investigate the root causes and vulnerabilities in PSM of chemical accidents and incidents, the following issues should be thoroughly discussed based upon the type of event involved.

For equipment failure events caused by employee inaction, root cause mining should explore the gap in company PSM according to the following questions: (1) Is a worker responsible for the equipment? If not, the job system is defective. (2) Is there a standard inspection and maintenance schedule? If not, equipment management is defective. (3) Do employees master the content of equipment maintenance and inspection? Otherwise, training is inadequate. (4) Is the content of equipment maintenance and inspection applicable? If not, equipment maintenance and inspection are defective. (5) Are equipment problems eliminated on time? If not, the problem-solving system is flawed.

For incidents caused by employees' operation errors, root cause mining should obey the following questions: (1) Are there operating procedures for this operation? If not, the operating procedure is defective. (2) Is the operating procedure correct? If not, the operational procedure is defective. (3) Do staff members understand the requirements of operational procedures? If not, training is inadequate. (4) Is there a verification process for complex operations? If not, the conduct of operations is a deficiency. (5) Is the employee capable of this job? If not, the process safety competency is defective. Through the above root cause discovery procedure, companies can better discover the loopholes in their PSM.

An impeccable accident database statistics platform can effectively motivate the Chinese chemical industry to learn from accidents to avoid similar problems. Both accidents and near misses should be uploaded to the platform, which should be promoted by the government and chemical associations. This will greatly aid in identifying root causes and fostering a robust safety culture. Moreover, these companies should not be punished for sharing accidents. The accident information should include the accident process, the cause of the accident, the suggested measures, etc., which should be released after analysis and confirmation by the company's safety management department.

4.4. Wide application of inherent safety

Accidents can effectively advance safety development and aid companies in identifying their vulnerabilities, but given the huge loss involved, this approach is the worst for enhancing safety. According to the accident study above, a safety strategy may fail because it is susceptible to factors, such as technology, system, human, and functional deterioration. Therefore, the fundamental strategy for enhancing China's chemical safety is to apply inherent safety to mitigate the impacts of chemical accidents. Intensification, substitution, attenuation, and simplification are typical strategies for inherent safety that can be applied throughout the life span of chemical production, including conceptual design, process development, design, operation, maintenance, and decommissioning. In China, there are more than 210,000 chemical companies, and more than 80% are small and medium-sized companies with antiquated technologies, obsolete machinery, and low levels of automation and control (Jiang, 2022). These companies should apply inherent safety strategies to improve their inherent safety level and achieve effective risk management and control. Inherent safety should be broadly promoted in all aspects of China's chemical safety management because it considers the concept of solving problems from the source. Although additional protective measures are widely considered to be outside the scope of inherent safety, the applications of inherent safety to the protective measure itself increase the reliability or effectiveness of the protective layer.

In addition, inherent safety assessment techniques have received much attention in academic studies but are rarely used by chemical companies in China (Jafari et al., 2018). Therefore, it is crucial to encourage the use of inherent safety evaluation methodologies for the progress of chemical safety in the chemical industry of China.

4.5. Promotion on the advanced safety management concepts

The current safety management approach in China emphasises using accidents to promote relevant work and views inspection and penalties as the main safety management tools (Jiang, 2022). For instance, all types of safety inspections on nitro chemicals and fines for unqualified firms are carried out quickly when an accident involving nitro chemicals happens. Such a safety management model is lagging and inadequate, while a risk-based safety management model should be suggested. It is because a risk-based safety management model can comprehensively and systematically identify hazards before any operator and device were harmed. Besides, risk-based management can also effectively account for economic and safety conflicts. Some examples are shown below. (1) The process operation procedures should be prepared based upon Hazard and Operability Analysis (HAZOP). (2) A risk-based preventive maintenance plan should be established in equipment management. (3) The detailed handling operations in the emergency plan should be based upon the worst credible accident scenario.

Promoting a deep integration of informatisation and industrialisation is the top priority for the safety management of the chemicals industry (Jiang, 2022). It is encouraged to promote risk analysis using big data, artificial intelligence, digital twins, and other computer technologies, such as strengthening the in-depth analysis and early warning of abnormal process data, establishing data-driven dynamic risk management which can be used in the entire life cycle of the production, transportation, and storage of hazardous chemicals.

5. Conclusions

This paper analysed the investigation reports of 14 major and particularly serious accidents in China to study the correlation among the causes of the accidents. The study observed that poor process safety culture, intentional violation (rule-breaking) of procedure, inadequate safety training, and illegal operations were the most frequent causes of accidents. Mapping these causes with PSM highlighted the significant gaps in the process safety culture, compliance with standards, the conduct of operations, process safety competency, and training & performance assurance. The results based on co-occurrence analysis indicate a strong correlation between the vulnerabilities of these PSM enterprises. Enterprises should pay attention to collaborative management among them. These deficiencies in the enterprise's PSM system show that the essential defects in China's chemical industry are a poor safety culture, inadequate accident investigation, inadequate training, and a lack of chemical safety personnel.

The chemical industry in China should make greater efforts on the following topics. The chemical company in China should make greater efforts to improve the positive safety culture. It is to be accomplished by emphasising clear process safety culture goals, safety leadership, adequate safety resources, and authority, safety work involving all staff, and actively identifying problems. The safety education and training of chemical engineers should be strengthened. Universities must be supported by government education institutions, and corporate leadership should encourage employee training. An internship in the chemical industry is recommended to enhance students' understanding of chemical safety knowledge. There should be a stronger emphasis on building university-industry partnerships. The industry should establish process safety indicators and regularly monitor and report these indicators. The industry should also practice robust accident investigation and root cause analysis protocols. The MORT model is highly recommended in the root cause analysis. This would provide endless opportunities for learning and improvement. The government and the chemical industry should brace the development of a common platform to report incidents and accidents with the root causes to enable deeper analysis and learning. Near misses should be actively uploaded to the platform. Inherent safety should be vastly used as the highest preferred risk reduction way. The inherent safety assessment should be well implemented in the chemical industry. The risk-based safety management system integrated with the process safety indicators is essential for effective PSM of the chemicals industry.

The limitations of this study lie in the scarcity of significant accident cases with detailed publicly available investigation reports. Conversely, there is a lack of sufficiently detailed and public investigation reports for numerous general or attempted accidents with higher quantity, thus hindering our analysis. Therefore, in the future, we aim to seek databases with abundant and detailed accident information, which may provide valuable safety enhancement recommendations for specific enterprises or industries through the use of this method.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psep.2023.06.040.

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