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Review

A Systematic Literature Review on Safety Research Related to Chemical Industrial Parks

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Abstract: The increasing demand for chemical products has driven the construction and development of chemical industrial areas, or so-called 'chemical industrial parks' (CIPs), but this has intrinsically raised the risk of major accidents. Therefore, it is significant and urgent to summarize the state of art and research needs in the field of CIP safety. In this paper, a keyword co-occurrence analysis of 116 scientific articles was conducted to support the classification of research topics in this field, then an overview of those research topics was presented to investigate the evolution of safety research with respect to CIPs. Specifically, the way that safety assessments are conducted, as well as how safety management and safety technology in such areas are classified and investigated, followed by detailed descriptions of representative methods and their contributions to CIP safety, are discussed. An integrated safety framework for CIPs is proposed to organize safety approaches and measures systematically. Based on the classification and analysis of studies on management, assessment, and technology related to CIP safety, the research trends and future directions and challenges are discussed and outlined. Those results are useful for improving theoretical method and industrial strategies, and can advance the safety and sustainability development of CIPs.

Keywords: chemical industrial park; review; safety management; safety assessment; safety technology; safety framework; trend

1. Introduction

The chemical industry has played a vital role in international economic developments, driving large-scale increases of the processing of chemical materials and the transportation between chemical companies [1–3]. Clustering of companies in industrial parks has become an efficient way to integrate the chemical industrial chain and has some positive effects on sustainability [4,5]. Moreover, collaboration also makes it more convenient for the implementation of Industry 4.0 in the chemical industry [6]. Unlike the traditional industrial areas, chemical industrial parks (CIPs) are geographically defined areas within which several independent chemical companies (processing, manufacturing, oil and gas, storage, logistic, etc.) are located. Those companies usually share infrastructure and even buildings, with no one company possessing the dominant position [3] (although there are exceptions). Currently, CIPs can be found around the world, and synergies and benefits of scale are created via collaboration and sharing of materials, services, information, and other matters.

Despite the many advantages of clustering, the massive scale of chemical substances and specific processes in CIPs may obviously significantly increase the potential threats to humans and the environment. Although cross-company major accidents in CIPs may be regarded as extremely low frequency, they should not be neglected due to their potential high consequence. For instance, on 21 March 2019, the massive explosion in Tianjiayi Chemical Co., Ltd., Xiangshui CIP, China, killed 78 people and injured more than 640, and caused a further 19.86-billion-yuan loss [7]. On 11 December 2005, a massive vapor cloud explosion struck the Buncefield fuel depot near Hemel hempstead, UK, causing 43 people to be injured and more than 20 installations damaged [8]. On 19 November 1984, a terrible explosion in the Mexican National Oil Company, Pemex, killed 650 people and damaged 48 tanks, costing more than 22.5 million dollars in losses [9].

Since large-scale cluster-related accidents may thus inflict heavy casualties and property losses, there is an increasing attention of governments and safety institutes to prevent and mitigate potential accidents in CIPs [2,10,11]. The United States of America, the European Union, and China are all regions with a lot of chemical industrial activities and hence, a large number of CIPs. In those regions, a series of regulations specifically about process safety (which is safety in chemical companies to avoid major accidents involving dangerous substances) have been promulgated [12–15]. Moreover, several research institutes, such as the American Institute of Chemical Engineers (AIChE), the European Joint Research Centre (JRC), the UK Health and Safety Executive (HSE), the Netherlands Organization for Applied Scientific Research (TNO), and the Chemical Industry and Engineering Society of China (CIESC), reacted quickly by developing innovative concepts and technologies to adapt to the risks in CIPs [2,16,17].

At present, some further new paths are being investigated. For example, the concept of 'Industry 4.0' originated from the fourth industrial revolution, facilitating the transitioning from conventional chemical processes into smart ones by adopting emerging technologies (e.g., internet, Internet of Things, big data, and artificial intelligence) [6,18]. Despite all the advances that have been made over the past decades, accidents remain very much present in the recent past. More seriously, the escalation of cross-plant accidents (domino effects) and accidents triggered by natural events (Natech events) are more likely to occur in CIPs through the presence of cross-plant effects. This situation has stimulated scholars and managers to further explore how to improve safety within CIPs, with the aim of risk mitigation and cost reduction.

Many studies have been conducted to investigate various topics related to CIP safety, such as those concerning hazard identification, risk management, and accident mitigation. Early research was focused on hazard identification, and some hazard identification tools (e.g., Hazard and Operability Analysis and Failure Mode and Effects Analysis) have been adapted to cluster safety [19]. In 2010, Heikkila and collaborators [3] modified the production paradigm and identified challenges for risk management in CIPs. A heightened interest has been raised to explore accident mechanisms in CIPs in order to advance this research field, coping with those challenges related to CIPs [20]. Some papers present the analysis of major accidents in CIPs [7,16], and in some, specific types of accidents are identified. In addition to conventional chemical industrial risks, companies operating in CIPs are facing external risks caused by cross-border effects in which domino effects [21] and Natech events [22] have attracted much attention by researchers and authorities due to their happening from time to time worldwide. The accident evolution has been discussed in certain studies, leading to the development of tools of safety management and assessment [1,3,5,21–23]. Nevertheless, several accidents still occurred. In order to further mitigate the accident consequences and minimize the losses, scholars started to be concerned about prevention measures and emergency response measures. For instance, some technical safety measures and their performance in accident mitigation have been discussed [1,23,24]. Besides, some studies focused on multi-plant emergency response, rescue route planning, allocation and distribution of emergency resources, and the like [2,3,10]. Despite the various research contributions, review papers about CIPs and their safety from an overall perspective, are absent. Nonetheless, it can be observed that the multi-plant aspect of CIPs is responsible for a diversity of research directions and publications.

Therefore, there is an urgent need to understand the process on the research field of CIP safety, identifying what are the main research topics in current research and possible directions and challenges of future studies. Literature review is an effective way to identify the hot topics and to systemize knowledge in a given research field. This paper is aimed at providing a concise overview of the existing status and latest research on the main fields of CIPs and safety. The most dominant safety models or tools and their contributions to CIPs are summarized, and a comprehensive framework for CIP safety is established. Finally, the research trends and future directions are outlined from the perspective of previous studies on CIP safety, which is significant for both safety research and prevention strategies of CIPs.

2. Methodology

To conduct the review of the current research status on safety related to CIPs, a three-stage systematic literature review methodology was adapted. The stages of this methodology included research questions formulation, data acquisition and extraction, and data analysis [22,23]. Firstly, the research questions were raised in line with the research objective illustrated in the introduction, as follows:

(1) What are the main research domains in CIP safety studies?
(2) How does the relevant research contribute to addressing the safety problems in CIPs?
(3) What are the current safety approaches or measures used in CIPs?
(4) What are the current gaps between state-of-the-art research and CIP practice?

Next, documents were extensively searched and collected from the Web of Science Core Collection, which is the most authoritative and widely used database in the world. The literature search was finished on 31 January 2020. The search was based on title, abstract, and keywords for the studies published between 2000 and 2020. Several keywords related to CIP safety were selected to form the search set, as follows:

- Topics: 'safety' or 'safe' or 'accident' or 'emergency' or 'vulnerability' or 'hazard'
- AND Topics: 'chemical park' or 'chemical industry park' or 'chemical industrial park' or 'CIP' or 'chemical cluster'.

This search found 229 results under different categories, which originated from different countries and regions. But not all results were actually related to CIP safety. Some articles with unrelated concepts, such as food safety, biological safety, and the like, could be searched due to the implicit "AND" operator in the Web of Science Core Collection. Therefore, those results were further refined manually to select the relevant papers based on a thorough examination of the information provided in the title and abstract. A final sample of 116 articles was selected for including in the review.

The last stage of the systematic literature review aims to provide a summary of current research in a better insight, for which a preliminary classification of the research domain was needed. In order to identify hot topics and topical trends in the research domain, a software for visualizing and exploring bibliometric networks, VOSviewer 1.6.15, was employed to conduct a keyword co-occurrence analysis. Figure 1 provides an overlay visualization involving keywords of retrieved documents. The items in Figure 1 are shown in different colors according to their publication years and the time mapping method is illustrated in the color bar on the bottom of Figure 1. In addition, the larger the sphere, the more frequently the sphere-related keyword occurs. As shown in Figure 1, fires, major accident hazard, overpressure, risk assessment, and protection are very frequent keywords in documents published before 2012. Since 2012, domino effect, vulnerability, accidents, hazard, management, and prevention have been popular keywords. The results highlighted that the publications related to CIPs safety are oriented to accident prevention and plant protection based on management and assessment methods. Recently, domino effects within CIPs have emerged as an intensifying topic, from which some related concepts, like vulnerability, have been derived.

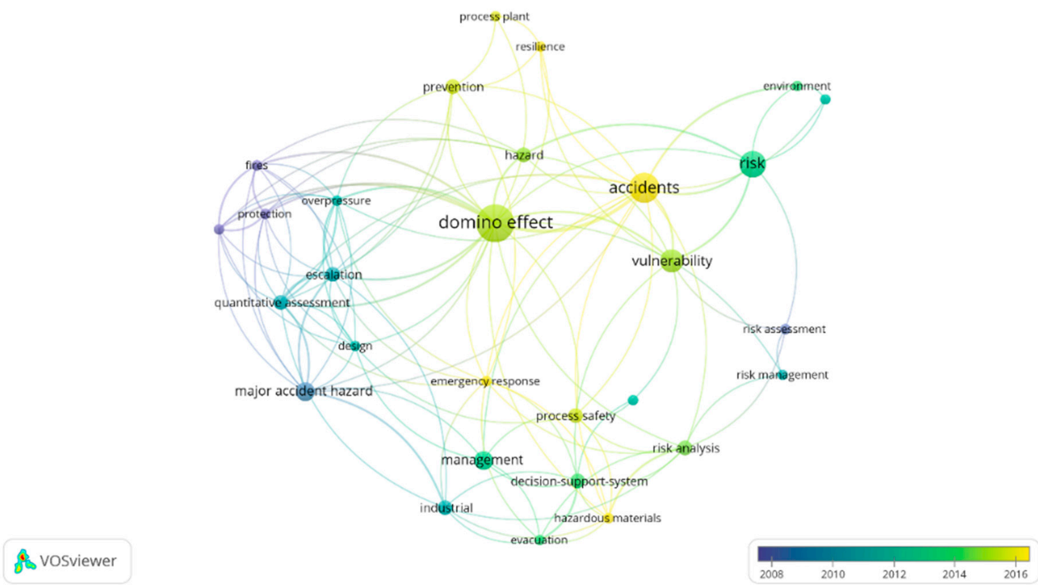

Figure 1. Overlay visualization of keywords in documents.

Therefore, a simple classification was performed according to the keyword co-occurrence analysis. The research topics that we found were (i) management approaches in CIPs; (ii) risk assessment methodologies used or proposed for CIPs; (iii) existing technology to prevent or mitigate accidents in CIPs. A classification (Figure 2) was further carried out for nine issues related to those three research topics. The management approaches included procedural management of regulations, collaboration management of multi-plants, internal management of chemical enterprises, and emergency management on a CIP level. For the second classification group, publications of assessment methodologies were divided into vulnerability assessment and risk assessment in accordance with the purposes and ideas of related studies. The third classification was based on the device roles in different accident stages, including the monitoring and alarming, prevention and mitigation measures, and the emergency decision-making system. Section 3 will present a detailed review of the documents based on the three classification groups described above.

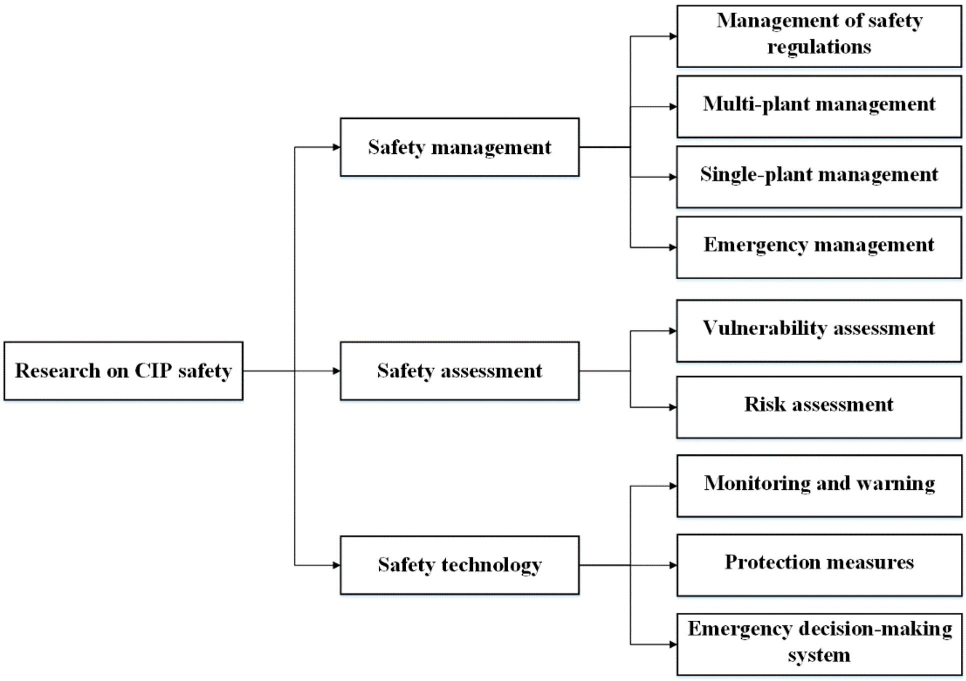

Figure 2. Classification of the research about chemical industrial park (CIP) safety.

3. Overview of CIP Safety-Related Studies

3.1. Safety Management

Safety management in CIPs aims to reduce the probability of an accident and its possible consequences using a series of regulations, strategies, systems, and procedures. Contributions on this domain have been focused on some aspects by considering policies-related, collaboration-related, enterprise-related, and emergency-related approaches. Section 3.1 identifies the research trends and gaps in the research of CIP safety management and classifies research according to its contributions.

3.1.1. Management of Safety Regulations

Chemical companies and their industrial activities are regulated by various regulatory agencies and compliance with many safety regulations and standards is required. A series of safety regulations are formulated in different countries to prevent and control major accidents where dangerous substances are involved. Those are: the regulations about process safety management (PSM) proposed by the Occupational Safety and Health Administration (OHSA) in the USA [25], the Seveso III directive in EU [14], and the AQ/T 3034-2010 in China [12,26]. The regulations are made by considering many safety elements, like safety training and compliance auditing. Nonetheless, many chemical accidents still occur, indicating that those regulations are not always able to prevent major accidents. Some reasons that can be thought of include: (i) there are some gaps in the contemporary regulations; (ii) extensive regulations from different government agencies may confuse the administrators of chemical companies; (iii) regulations sometimes are broken intentionally or due to negligence.

Most of the past regulations have been revised or more provisions have been added based on the lessons learned from past accidents. For instance, in 1996, the new Seveso I Directive replaced the Seveso I Directive from 1989, filling some gaps of regulations, such as the thus far lacking regulation on potential domino effects in chemical clusters. The major Mexico City accident, which happened in 1984 and is still today the most deadly domino effect that ever happened worldwide, was the reason for this. In 2012, the Seveso III Directive replaced the Seveso II Directive and the hazardous materials classification was, for instance, updated [14,21,26]. After the Gu-mi accidents, Korean laws and governing regulations for hazardous chemical materials have been improved, where their enforcement was enhanced, especially for toxic substances [27]. It is noteworthy that those amendments of regulations only represent the current knowledge of agency and consultants. However, as circumstances change constantly, new risks sometimes arise in CIPs, revealing new (or old) deficiencies in the regulations. In the last two decades, for example, Natech events have been recorded in Europe [16,17]. Besides, data insecurity problems emerged during the implementation of Industry 4.0. All these emerging facts and novelties have thrown down some new challenges to the industry regulators [6]. However, current regulations don't explicitly address those emerging risks linked to the new changing world and still need to be further improved [14,16].

Furthermore, a large number of safety regulations make it harder for CIPs to comply with those rules. As an example, in China, there were around 635 chemical industry parks in 2018. There were more than 900 safety control regulations or national standards to address chemical safety problems in 2010 [28,29]. It may therefore sometimes be difficult for managers of chemical plants to identify the regulations that they really need [30,31]. Furthermore, CIPs may be important targets for terrorists, with possible external domino effects and devastation via cross-border consequences [32–34]. Therefore, obviously, laws and regulations for CIPs should further be developed considering both safety and security.

3.1.2. Multi-Plant Management

Clustering creates synergistic benefits by providing shared industrial infrastructures and other resources. However, multi-operator sites or CIPs also raise some safety and security issues owing to the installation interconnections and closeness within the site locations [35,36]. Therefore, developing cooperation and collaboration management between separate plants so that overall safety integrity would be optimized and preserved is good practice. Many researchers confirmed this view. Reniers [37] indicated that enhancing multi-plant collaboration could lead to a 'CIP safety culture', since free and open communication under a well organizational structure will promote chemical companies learning from each other and the integration of individual plant safety culture. Reniers and Amyotte [38] stated that collaboration can not only enhance the safety and security level of individual chemical enterprises, but also elaborate on the sustainability of CIPs with long-term competitiveness. They suggested that cross-plant collaboration can be extended to economic, environmental, information, and social dimensions. Tupa et al. [39] highlighted the importance of information exchange and close cooperation between companies for adequate risk management within Industry 4.0. High-level collaboration in information can form a real-time optimized and self-organizing safety network. Studies investigating the collaboration of chemical plants can be found in Table 1.

A cluster council can play an important role in the continuous safety improvement of CIPs. Reniers et al. [40,41], for instance, indicated that strategically complementary investments of plants belonging to a CIP can be more safety-effective, especially with respect to domino prevention. In the same line, strategic safety decisions have been discussed using game theory [42,43]. Besides, Reniers et al. [44] pointed out that the present strategic cooperation within CIPs only deals with business opportunities or environmental and energy issues and not with enhancing safety. Further proactive strategic cooperation and improvements are thus needed to tackle safety issues, especially in the specific domains of domino effect prevention and Natech safety.

Table 1. Recommendations for CIP management improvement.

	Author(s)	Aspect	Main Work	Recommendations
1	Reniers et al. (2009) [40]	Organization structure and responsibilities definition	Built a CIP organization framework and safety management system	(1) Establish an on-site cluster council, including confidential and non-confidential parts (2) Consider the external domino effects of plants (3) Strengthen information commutation and feedback between council and companies
2	Gaucher and Dolladille (2010) [35]		Highlighted the main issues for managing information risk in CIP	(1) Establish an on-site risk management agency (2) Encourage efficient contracts between different companies in CIP (3) Flexibly revise the contracts according to the actual situation
3	Heikkila et al. (2010) [3]		Developed a cooperation model in CIPs based on a Finland project	(1) Define the responsibilities of suppliers, distributors, and other areas in the CIP level (2) Develop the cooperation and common agreement of multi-plants
4	Reniers (2010) [41]	Safety investigation and strategy	Discussed the safety policy within a two-company CIP using Nash-equilibrium	(1) Cluster council can guide the safety investigation to obtain socioeconomic optima (2) Strategically complementary investments of multi-plants are more economical and effective than single plant investments (3) Local government can stimulate enterprises to seek the socioeconomic optimum via some incentives
5	Pavlova and Reniers (2011) [42]		Analyzed the strategic cooperation on safety and security within CIP levels via game theory	(1) Develop a two-stage sequential move game led by cluster council for safety cooperation (2) Establish a subsidy system at minimum expense based on Nash equilibrium (3) The multi-plant cooperation can be set up in the proposed stepwise roadmap
6	Zhang et al. (2019) [43]		Proposed a method to realize strategically scheduling security patrols by employing the game theory	(1) Deploy security patrolling at the CIP level besides the countermeasures (2) The patrolling strategy based on the Stackelberg equilibrium shows better performance than other patrolling patterns

3.1.3. Single-Plant Management

The earliest safety management approach for single-plants can be traced back to the end of the 20th century using the safety management system (SMS) to control major accidents [21,26]. As a result, the use of SMSs has been emphasized in several relevant articles [26,45–47]. But, as Hasle and Limborg [48] indicated, the manager of an enterprise, especially in a private organization, often discounts the importance of safety management due to a bad safety culture and an economic survival pressure. Some studies presented advantages and tools of safety management from an economic perspective. For example, Lee et al. [27] argued that safety management has great significance in enterprise development based on the accident investigation of the Korea Gu-mi and Ulsan accidents. Safety management is able to reduce losses, waste, and expiry of materials. Besides, Reniers and Van Erp [49] addressed cost–benefit analysis for safety investments in order to optimize operational safety decision-making, covering both risk assessment and financial thinking.

Other studies have contributed to providing countermeasures supporting the implementation of SMSs. To this regard, McGuinness et al. [50] proposed a step-wise generic guideline for enterprises. This guideline suggests that the management rules can improve according to risk assessment reports. Bragatto et al. [10] also discussed how to build and improve safety management rules. A safety net model was developed to connect the regulations, workers' experience and audits, and to dynamically revise management rules. Besides, safety management should take corresponding measures after classifying and categorizing the risk sources [51]. Since several studies proposed improvement measures, a comprehensive framework of SMS has been established by Ma and Chang [52]. Recently, Accou and Reniers [53] developed a safety fractal analysis (SAFRAN) model for discussing how a

SMS can learn and be changed based on an accident investigation. These researchers have identified the key factors of SMS in a structured way in order to promote a sustainable development in safety performance, as shown in Figure 3. The cycle in Figure 3 would encourage employees to commit to the safety goals of a company through peer observation and feedback, which is helpful for the creation and growth of 'plant safety culture'.

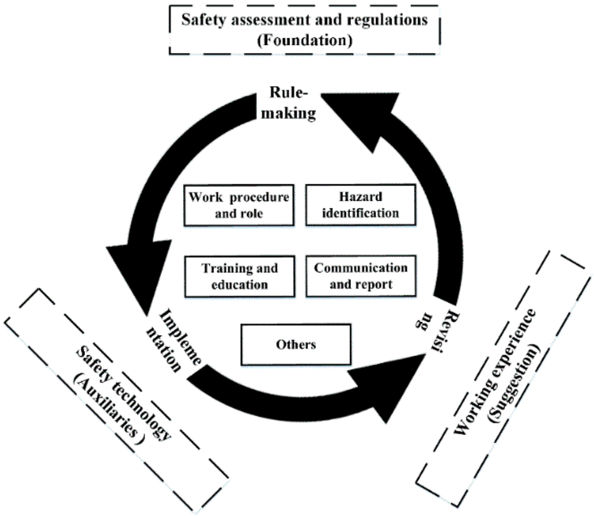

Figure 3. Framework of safety management system in a single plant [52,53].

3.1.4. Emergency Management

Emergency management is essential to mitigate and prevent catastrophic consequences [54–57]. Furthermore, emergency management in a CIP (Figure 4) plays an important role in guaranteeing its sustainability and safety [55,58,59]. Due to uncertainties related to the dangers of hazardous materials and human factors, emergency management within a CIP needs to pay more attention to systems management and operational research [55].

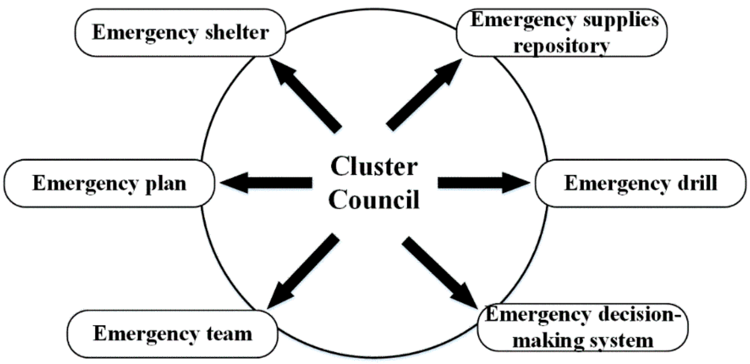

Figure 4. Elements of emergency management in a CIP [55,58,59].

In the case of the optimization of the allocation of emergency resource repositories or shelters on CIPs, it is not so easy to cover the emergency requirement of multi-plants since the multi-objective optimization is a typical NP-hard problem (a problem is NP-hard if every problem in non-deterministic polynomial is polynomial transformable to it. The optimization of the allocation of an emergency site in order to cover the requirement of multi-plants can be formulated by the multi-objective traveling salesman problem and multi-objective knapsack problem, which are well-known NP-hard problems) [58,60–62]. Therefore, some studies have contributed to addressing this problem by developing new algorithms. For instance, Men et al. [58] proposed an optimization algorithm to allocate emergency resources for covering the requirement of all demand points. However, the location optimization in CIPs is rather complex due to all kinds of uncertainties related to human, material, and environmental factors involved in the requirement of emergency resources. For example, the emergency reserve strategy strongly depends on risk perception about accidental areas. Some advanced methods (e.g., probabilistic approaches and stochastic programs) that, if applied together, would obtain a clear risk result, thereby considering nonlinearity and randomicity of accidents, can be suggested [63]. Besides, how to ensure the timeliness of emergency actions and human-related challenges with respect to the location selection has also been the topic of previous research [64,65]. Considering the quick response of emergency responders, Feng et al. [64] established a location selection mathematical model using a dynamical iteration algorithm. The optimization objective is to shorten the response time associated with an accident within a CIP. The decision-making model on the allocation of emergency supply repositories was more scientific with the limited cost and short transport length.

In addition to the location selection, as shown in Figure 4, the joint evacuation drills and emergency plans are also the key parts of emergency management. The conventional procedures of those works are illustrated in some laws or regulations, like "Management Measures for Emergency Plan of Work Safety Accidents" in China, "Emergency Planning and Community Right to Know Act" in the USA, etc. However, achieving fully optimized emergency response is still a challenging work since it is also related to organizational and deployment problems. To address the problem of alert levels within CIPs for instance, Hosseinnia et al. [54] developed a multi-plant emergency response decision-making tool for CIPs based on a matrix method to prevent and mitigate domino effects. To enhance the emergency capability of CIPs, more intelligent and strategic emergency decision-making methods should be explored, avoiding subjective issues in the emergency process.

3.2. Safety Assessment

Safety assessment is the prerequisite for risk communication and risk understanding [66]. Therefore, vulnerability and risk calculation in CIPs should be a major topic to support safety strategies. The vulnerability assessment can provide a prejudgment for safety managers within CIPs when the risk-related information is lacking. Safety assessment methodologies have been developed to identify vulnerable or high-risk targets in CIPs aiming at accident prevention. Section 3.2 presents these contributions and groups the studies according to their characteristics and purposes.

3.2.1. Vulnerability Assessment

Vulnerability assessment of CIPs can be considered from three aspects: area vulnerability, human vulnerability, and installation vulnerability. Table 2 presents an overview of the existing vulnerability assessment methodologies.

Table 2. Overview of the vulnerability assessment methodologies for CIPs.

	Study	Aim	Methodology	Contribution
1	Tixier et al. (2006) [67]	Chemical industrial area vulnerability (fire and explosion)	Implement the vulnerability indicators within GIS to accomplish automatic calculation	(1) Combine the expert judgment and hierarchical structures to characterize area vulnerability (2) Visually display area vulnerability around the industrial site (3) Provide an available operational tool for CIP managers
2	Li et al. (2010) [68]	Human vulnerability (fire or explosion)	Aggregate the physical vulnerability and social vulnerability to an integrated index via the layer superposition function of GIS	(1) Develop a conceptual model for human vulnerability to chemical accidents in CIP (2) Highlight the role of vulnerability assessment for prioritizing safety management (3) Human vulnerability is visualized in GIS through layer superposition

Table 2. *Cont.*

	Study	Aim	Methodology	Contribution
3	Landzano et al. (2014) [69]	Pipeline vulnerability (earthquake)	Analyze the seismic vulnerability of buried pipelines based on historical data	(1) Discuss the failure mechanism of pipelines in earthquakes through a multidisciplinary analysis (2) Derive the seismic vulnerability formulas and failure thresholds
4	Khakzad and Reniers (2015) [70]	Chemical plant vulnerability (domino effects)	Map the plant vulnerability using graph theory after representing the possible cascading effects as a directed graph	(1) Use the vertex-level closeness and betweenness to map plant vulnerability subject to cascading effects (2) The most vulnerable plant layout can be identified using the graph theory
5	Argenti et al. (2016) [71]	CIP vulnerability (external acts)	Evaluate CIP vulnerability under protection systems using Bayesian Network	(1) Discuss the role of probabilistic method in vulnerability assessment (2) The likelihood of attack success has been considered in the vulnerability assessment
6	Yan et al. (2016) [72]	Structural vulnerability (fire or explosion)	Meta-quantitative evaluation of the facilities' vulnerability using vulnerability index	(1) Establish the index system and scoring criteria for structural vulnerability (2) Search the vulnerable link in CIP through sort the vulnerability indexes
7	Khakzad et al. (2016) [73]	Installation vulnerability (domino effects)	Analyze the domino vulnerability of hazardous installations based on graph theory	(1) Identify the most vulnerable installations during domino effects by employing the centrality metric (2) Provide a quick yet reliable vulnerability assessment method to deal with the complex accident scenarios
8	Fatemi et al. (2017) [74]	Human vulnerability (toxic material leakage)	Estimate the vulnerability of human living near chemical installations based on fuzzy Delphi-AHP method	(1) The indicators of human vulnerability have been divided into social and physical sets (a total of 19 indicators) (2) The vulnerable group has the greatest impact on human vulnerability when facing chemical accidents
9	Basco and Salzano (2017) [75]	Tank vulnerability (tsunami)	Develop probit function to evaluate vulnerability of tank	(1) Establish the vulnerability model for tank under the impact of tsunami (2) Verify the vulnerability function using historical data
10	Khakzad and Van Gelder (2018) [76]	Tank vulnerability (flood)	Assess the vulnerability of tank via Bayesian parameter learning	(1) Develop the limit state equations for different failure modes (2) Integrate individual failure modes to obtain a vulnerability value through Bayesian network
11	Chen et al. (2019) [77]	CIP vulnerability (multi-hazard)	Quantitatively assess the CIP vulnerability in a multi-hazard scenario using cellular automata	(1) Explore the CIP vulnerability theory for multi-hazard (2) Define vulnerability level of multi-hazard in CIP (3) Vulnerability partition of CIP can be visualized in GIS
12	Ardalan et al. (2019) [78]	Human vulnerability (toxic material leakage)	Improve Fatemi's method by introducing the vapor dispersion	(1) Social vulnerability indicators have higher weight than physical vulnerability indicators (2) The spatial factors such as the absolute distance and type of living place area have a significant effect on human vulnerability (3) Human vulnerability is displayed in GIS
13	Li et al. (2019) [79]	Tank vulnerability (coupling of fragment impact and pool fire)	Numerically investigate the mechanical vulnerability of cylindrical tanks	(1) Discuss the relationship between external loading and structural resilience (2) The plastic adaptation under external impact is considered in the physical model (3) Provide the critical failure criterion to understand tank vulnerability under external coupling accidents
14	Chen et al. (2019) [80]	Installation vulnerability (domino effects)	Dynamically evaluate installation vulnerability exposing to domino effects using dynamic graph theory	(1) Develop a graph update algorithm to dynamically predicate the domino propagation (2) Consider the performance of safety barriers (3) Model the spatial–temporal feature of domino effects

Table 2. *Cont.*

	Study	Aim	Methodology	Contribution
15	Jiang et al. (2019) [81]	Tank vulnerability (domino effects)	Assess the vulnerability level of tank in a multi-accident scenario using index evaluation	(1) Create the formation mechanism of multi-source coupling accident (2) Use risk matrix, complex network, etc. to assign index weight
16	Yang et al. (2020) [82]	Tank vulnerability (flood)	Evaluate multi-parameter vulnerability using logistic regression	(1) Develop the parameterized vulnerability models for extensive tanks and floods (2) Propose vulnerability magic cubes to analyze the effects of key parameters on vulnerability (3) The critical failure conditions can be obtained from the cube

The overview in Table 2 clearly shows that layer superposition and graph theory are the main methods of area vulnerability assessment. The 2D or 3D vulnerability map in Geographic Information System (GIS) as a preliminary tool can provide an intuitive insight to screen dangerous areas within CIPs. The earliest visual vulnerability map related to CIPs was given by Tixier et al. [67]. According to the vulnerability analysis of different areas, the detailed vulnerability index can be automatically integrated with GIS to suitably manage CIP risks. However, the vulnerability of CIPs not only depends on the inherent dangers of chemical plants, but also on possible escalation effects and on safety measures. As a result, the corresponding contributions have been made by several scholars to improve the accuracy of vulnerability results [70,71]. Recently, CIP vulnerability under possible inter-related hazards has been investigated to ensure a better apprehension of its safety status [77].

To explore human vulnerability with respect to chemical accidents, some specific models have been developed. As Table 2 shows, vulnerability indexes, including social and physical factors, can adopt multi-factors of human vulnerability well [68,74,78]. The weighing index can partially address the uncertainty related to human behavior. However, as Ardalan et al. [78] noted, the index method still needs to be improved since the assessment relies heavily on the data quality about the information and distribution of people.

In order to protect process equipment and support for quantitative risk assessment (QRA), probability models have been proposed to assess the vulnerability of installations. Except for a simple value, the vulnerability results can be presented in a curve way. This work was later enriched with studies focusing on possible domino effects and Natech events, to address the challenges related to CIPs. Seismic and flood vulnerability curves have been developed in some studies [69,75,76]. However, a single parameter cannot show the damage behavior due to complex disturbances. In this sense, later studies have been carried out for multi-factor coupling effects on equipment vulnerability, and also corresponding evaluation tools have been developed [81,82]. In recent years, dynamic assessment methods were developed to explore the temporal change of an installation's vulnerability, especially for the case of domino-related studies [80].

3.2.2. Risk Assessment

Risk analysis and assessment are dominant research topics in process safety publications since the 1970s, possibly partly due to the occurrence of major accidents from time to time [2,83–85]. It should be noted that possible escalation effects and Natech events may amplify the complexity of CIPs since many more damage vectors are potentially generated following the evolution of accident scenarios. Many researchers have made contributions to advance risk assessment approaches aimed at fitting complex situations about CIPs. Section 3.2.2 presents current assessment approaches on CIP-related risks where three categories are distinguished: numerical approaches, software-based approaches, and graph-based approaches.

(1) Numerical approaches

A risk index method has been developed to characterize multi-objective risk associated with CIPs in a specific value via hierarchical analysis. Chen et al. [86] developed an index system to evaluate CIP risk based on catastrophe theory. In this study, the risk level was divided into five stages with the aim of supporting prevention decision-making. Some mathematic tools, like data mining [87], whitening function of grey group [88], and the structural importance of fault event tree [89], were used to re-extract the weighs distribution of risk indexes in order to make the index-based evaluation more scientific and convenient. However, the indicators tool hardly provides a uniform criterion for risk assessment due to its nature [90]. In other words, the risk values based on risk indicators may span over a risk level among different evaluators for the same CIP.

To support risk management within CIPs, Meng et al. [91] used information-diffusion theory to calculate the environmental risk and to depict a spatial partitioning risk map. In the same sense, Shao et al. [92] developed a regional environmental risk physical model to identify high-risk areas within CIPs. The physical mechanisms of leakage accidents were considered through the analysis of dispersal patterns and migration models of hazardous materials. More importantly, specific safety distances can be obtained according to the assessment [93].

In recent years, domino effects and Natech events have obtained increasing attention in publications. Numerical tools and equipment-specific fragility models derived from installation vulnerabilities have been used to estimate the accident probability. Zhou and Reniers [59] proposed a matrix-based analysis approach to analyze the synergistic effects in accident escalation by a matrix iteration algorithm. This approach can determine the likelihood of domino effects based on the equipment-specific probit model for fire. Liu et al. [94] developed an area risk assessment model based on a frequency estimation approach, addressing multiple escalation vectors (e.g., heat radiation, blast waves, and fragment action) and the risk associated with escalation. Besides, using the fragility model for installations subject to natural hazards, the QRA framework has been further extended to assess Natech risk within CIPs [22].

(2) Software-based approaches

Many programs or software based on accident analysis, for instance, DNV, CASSTQRA, RISKCURVES, have been developed to assess potential consequences of plants or installations to the surroundings, avoiding the complexity and possible huge workload of numerical approaches. Although software only requires some given inputs, they are considered as a promising tool for potential complex accidental scenarios due to their strengths in accident simulation. Li and Wang [90] implemented the QRA with CASSTQRA software to analyze the risk distribution within the Yangtze River CIP in China. The individual risk contours and societal risk (F-N curve) have been calculated and drafted to support the safety planning of the CIP.

With the increasing attention of domino effects, some analytical methods based on the so-called 'maximum credible accident propagation sequence' were coded for estimating the escalation probability and potential consequences. Khan and Abbasi thus developed the DOMIFFECT software for domino effect analysis, able to model the potential consequences of different domino scenarios [21].

To mitigate the impact of natural hazards on CIPs, the conventional Natech QRA framework was established and specific Natech events were discussed in some studies [82,95–98]. The first Natech QRA methodology was proposed by Antonioni et al. [96]. In their study, the QRA methodology for earthquake-related industrial accidents was developed based on an equipment vulnerability model. The individual and societal risk were determined using Aripar-GIS software. Application of the GIS-based software in an actual CIP is able to provide high-risk installations according to the risk curves. This work was further extended to assess flood Natech scenarios. The possible multi-unit leakage accidental scenario was considered in the risk assessment and was implemented in Aripar-GIS [97].

(3) Graph-based approaches

There are various hazardous units with a variety of accidental probabilities in any CIP, especially when potential domino effects are considered. In other words, some units more easily lead to accidents while other units tend to facilitate the propagation of accidents. The higher-order domino effects are not easy for numerical approaches and software-based approaches due to the need for large computation time and a high amount of used parameters. To address this problem, these units are usually represented by some nodes and are connected by some weighted arcs in a graph. As a result, graph-based approaches provide a framework to explore escalation routes and quantify the propagation uncertainty based on some mathematical theories.

Bayesian network (BN) and Petri net as powerful probabilistic graphical tools were used in the quantitative analysis of uncertainty to support risk assessment. Yang et al. [98] proposed a BN-based probability prediction method to model the accident evolution and to estimate the probabilities of accident chains triggered by lightning. Two case studies derived from the actual layout of crude oil tank farms demonstrated that three-order and higher-order propagation is possible, especially when it concerns domino effects caused by Natech accidents.

Different from the static graph-based approaches as mentioned, the dynamic approaches are developed to model the dynamic evolution and to estimate the accident probabilities at different times. Kamil et al. [99] proposed a generalized stochastic Petri net model that is able to model domino propagation and accident likelihood. This method can capture the time-dependent failure behavior of process equipment related to synergistic heat loads. Zeng et al. [100] demonstrated a dynamic risk analysis method for fire-related domino effects. The method uses Dynamic Bayesian Network (DBN) to model the spatial-temporal evolution of escalation effects and calculate the dynamic propagation probability. The probability results are meaningful to support risk reduction via the management of safety barriers.

3.3. *Safety Technology*

The role of safety technology is not only providing the protection of assets, but also preventing or mitigating accident escalation. In the field of risk prevention, studies focus on discussing the performance of safety technologies and on providing recommendations for prevention strategies. Current technologies for preventing and controlling industrial accidents include monitoring and warning technology, protection measures, and emergency decision-making systems.

3.3.1. Monitoring and Warning

Chemical processes of major hazard installations (MHIs) pose potential threats to CIPs. Parameter fluctuations in the operation of MHIs may lead to accidents. Monitoring and warning technology aims to monitor the vulnerable parts of chemical processes and to alarm people once a leakage occurs in order to avoid minor events that could lead to major accidents [2,44,89,101]. Application of monitoring and warning techniques allow timely and prospective safety actions and are widely accepted in CIPs. In terms of a monitoring system, the accuracy of the observed data mainly relies on the monitoring points. However, the arrangement of large-scale monitoring points is very expensive in most cases. Li et al. [102] suggested using the unmanned aerial vehicle to build a dynamic monitoring network in CIPs. They developed a source tracing algorithm based on game theory and applied it in the Shanghai CIP to improve the monitoring system. To reduce the required additional investment as much as possible, preliminary optimization analysis is necessary. Some mathematic tools, like particle swarm optimization algorithms, are used to determine a deployment plan for monitoring points [103,104].

With technology development, an intelligent monitoring system related to Industry 4.0 has been adapted for real-time monitoring of MHIs [105–107]. Kong et al. [107] developed a data-driven warning method for CIPs, introducing information technology to the monitoring system to achieve early-warning. Those authors highlighted that identification of false alarms needs to pay more attention in future research. Geng et al. [108] developed a fuzzy clustering ranking algorithm to group and rank the alarm information. Optimizing alarms of monitoring variables, based on operating MHIs, is more practical in a real CIP. In the same line, Tian et al. [109] proposed a clustering analysis based method for alarm optimization using the ant colony algorithm. Their objective was to adjust the alarm thresholds to solve false alarm issues due to multivariable of chemical processes. However, those algorithms can't realize full dynamic alarm optimization in accordance with the operation of MHIs since they are still offline methods.

3.3.2. Protection Measures

The prevention and control of chains of events, being secondary or higher order damages of chemical installations, is important when CIP safety is considered [2,21,110,111]. Prevention and protection measures are evidently an important part of the prevention strategy. The current safety measures include inherently safer design (ISD), prevention and protection barriers, and combined measures.

(1) Inherently safer design

ISD with the aim of removing hazard sources has been effective to maintain system safety since the 1980s [112]. Khan and Amyotte [113] reviewed the applications of ISD on accident prevention with respect to offshore oil and gas activities. They emphasized that the application of ISD at the design stage of chemical processes yields the best results. In the Hsinchu Science Park, Taiwan, ISD has been applied for high-tech chemical processes, which significantly reduced accident rates [114]. Besides process design, ISD-based optimization is also widely used in layout design within CIPs to avoid possible escalation effects [115]. Cozzani and collaborators [116,117] proposed the use of escalation thresholds for different accident scenarios based on the analysis of major accidents involving domino effects. They identified inherent safety actions with respect to safety distances to support domino prevention in the early-design of plants or CIPs. Those ISD measures may be the most effective and straightforward ways to prevent accidents, avoiding the initiation of an accident or terminating its propagation. However, if installations have been built, it's impossible to make a major layout change or easily replace equipment. Therefore, add-on prevention and protection measures have been proposed to mitigate the potential consequences of accidents.

(2) Prevention and protection barriers

Add-on prevention and protection barriers are used to reduce either the probability or consequences of accidents. In particular, their roles in escalation prevention include restricting the domino propagation, mitigating the possible consequences of accident escalation, and increasing the time to failure (*ttf*) of chemical installations [80,100,118,119]. In recent years, studies on prevention and protection barriers have focused on discussing their protecting performance against possible domino effects, especially fire-related ones.

Chen et al. [80] analyzed the impact of add-on barriers (e.g., sprinkler system or fireproof coatings) on the residual *ttf* of target units and developed a dynamic vulnerability assessment methodology considering the temporal performance of safety barriers. The authors concluded that safety barriers can effectively prevent, control, or mitigate undesired events. However, the performance of safety barriers also can be affected by external factors, such as harsh environments associated with Natech events. Those external factors, such as wind and floodwater, may reduce the availability and effectiveness of safety barriers. To address the uncertainty and complexity induced by Natech events, Misuri et al. [110] assessed the performance of 16 types of add-on safety barriers exposed to Natech events through expert elicitation procedures. Their results show, for instance, that passive barriers are more resilient in case of earthquakes but that they are more vulnerable to floodwater.

(3) Combined measures

Reniers et al. [38] indicated that the integration of design-based principles and safety measures can build a truly safer CIP. In the same line, Cozzani et al. [117] argued that the integration of inherent safety criteria with add-on safety barriers is a promising route for domino prevention.

Janssens et al. [111] evaluated the delays of *ttf* and economic losses associated to the worst-case accident scenario under a different safety barriers allocation plan. They indicated that the effectiveness of combined protective barriers will exceed the single barrier due to possible interaction effects. Zeng et al. [100] discussed the performance of combined barriers (the sprinkler system and fireproof coating) on domino mitigation from the probabilistic perspective. After an analysis of propagation probabilities, they found that the combination of add-on barriers can effectively decrease the probability of a domino chain, even impede domino propagation. Finally, a five-level hierarchical framework has been provided by Jia et al. [120], in which different safety techniques (e.g., safety design and layer-of-protection) are combined to pre-control industrial accidents and possible domino effects.

3.3.3. Emergency Decision-Making System

Emergency response is an immediate and rapid movement process of people and resources. However, emergency decision and response tasks are rather complex due to the uncertainty related to human, environment, and emergency resources involved in the process of emergency response. The emergency decision-making system (EDS) is designed to properly and proactively cope with accidents and to provide intelligent planning and decisions via virtual emergency process simulations [6]. The emergency workflow based on EDS (Figure 5) includes: (i) a monitoring system or on-site staff alarms; (ii) an emergency command center identifying alarming information and offering emergency plans to guide emergency actions; (iii) emergency resources supporting emergency tasks; (iv) the effects of emergency response being evaluated and feedback being provided for the system.

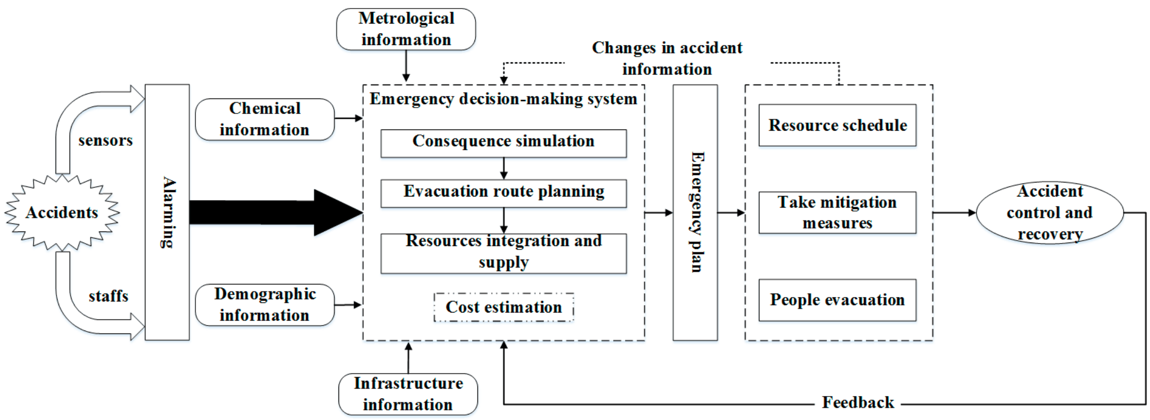

Figure 5. Emergency workflow using emergency decision-making system [121,122].

Although information technology (IT) is widely applied in the process industries to visualize emergency process, the optimization of evacuation paths and system status is still very challenging due to the complexities and uncertainties associated with multi-objective (plants and humans) problems within a CIP [121–126]. To optimize multi-objective emergency evacuation in case of a major accident, Georgiadou et al. [125] developed a method based on the evolutionary algorithm, minimizing the potential health effects and the socioeconomic impacts of the emergency plan. The presence of associated uncertainties of accident evolution was not fully considered, thus the proposed method is applicable with no or minor changes in some single specific accidents.

In recent years, many advanced works have been done to explore emergency decision-making considering multi-objective optimization under uncertainty, their contributions are demonstrated in Table 3.

Table 3. Contributions of microscopic models on emergency decision.

	Author(s)	Accident Scenario	Model Description	Contributions
1	Shen et al. (2015) [127]	Toxic release accidents	Developed a conceptual decision system using the network flow model that considers: (1) leakage information (2) weather condition (3) distribution and velocity of evacuees	(1) The spatial distribution of toxic concentration in multi-source release accidents can be simulated (2) The evacuation scope under toxic release accidents can be reported in detail (3) Authors concluded the shortest route may be not the best route in leakage scenario
2	Lovreglio et al. (2016) [128]	Toxic release accidents	Developed a dynamic route planning method considering human behavior: (1) gas dispersion is simulated by FDS (2) crowd evacuation is modeled using Pathfinder (3) the health impact rate is calculated by the Haber's law	(1) Real-time human behaviors are simulated by agent-based approach (2) The absorbed dose of toxic gas when people evacuation can be calculated (3) The case study proved that the simple linear movement assumptions in static methods are not characteristic of people evacuation
3	Cao et al. (2017) [129]	Toxic release accidents	Established an integrated emergency response model based on CA, which includes: (1) toxic gas dispersion sub-model (2) dynamic consequences evaluation sub-model (3) evacuation route selection sub-model	(1) Three sub-models can run simultaneously and provide real-time results for emergency decision (2) The integrated model can improve the efficiency of emergency response (3) The improvement of EDS provides a helpful reference for emergency decision model of other types of accidents
4	Chen et al. (2018) [130]	Pool fire and toxic release accidents	Proposed a two-way route planning method using Dijkstra's algorithm, which includes: (1) the dynamic grid environment model (2) a two-way route planning model (3) intelligent obstacle avoidance model	(1) The emergency rescue and emergency evacuation are simultaneously considered in the method (2) The method is visually on GIS with the agents move (3) The possible road conflict due to one-way planning is avoided
5	Rebeeh et al. (2019) [131]	Fire accidents	Established a framework for quick emergency response that considers: (1) environmental condition (2) population factors (3) surrounding industrial facilities	(1) The framework combined the location hazard index and the response time optimization model (2) The resource inter-transfer is simulated to minimize waste of emergency resources (3) The framework would improve resource allocation and response plans to accidents in CIPs

Some dynamic risk-informed algorithms for decision-making were developed to explore the impact of accident evolution on the emergency process, especially when the conventional model is not sufficient to simulate multi-source accidental scenarios [127,129]. Cao et al. [129] emphasized that evacuation route planning can be further developed by introducing other uncertainty factors, such as the level of congestion and the behavior of evacuees. To this regard, Lovreglio et al. [128] analyzed the temporal causality between gas dispersion and people evacuation. In addition, those authors highlighted the importance of agent simulation that could contribute to a better decision-making effort. Later, Chen et al. [130] proposed an agent-based route planning method, generating a two-way optimum plan, avoiding possible road conflicts of emergency rescue and evacuation. In addition to the route optimization based on risk perception, Rebeeh et al. [131] proposed an index-based emergency decision model for the supplementation of emergency resources, reducing the response time and accident risk. The study of an industrial case demonstrated that the resource supplement function could be integrated into the EDS, improving the operational performance of emergency response.

4. Discussion

4.1. Safety Framework for CIP

Although scholars have made contributions and present recommendations in many safety-related fields, development of a comprehensive safety framework for CIPs remains a major challenge since it is a complicated system engineering problem. The dependence of safety on a single measure usually is undesirable and ineffective. Safety management on a multi-plant scale is a relatively high-level approach, and is all not easy, as we noticed that implementations within some current CIPs are disorganized (discussed in Section 3.1). In addition, safety assessment approaches and safety technology have evolved significantly over the past two decades and partly have already been applied in the ordinary activities of CIPs. Thus, a good systematic safety framework is needed to organize those related safety measures to avoid overlap and excess of safety activities and to clarify the future directions of development. To address the proposed, an integrated safety framework for CIPs (Figure 6) has been established.

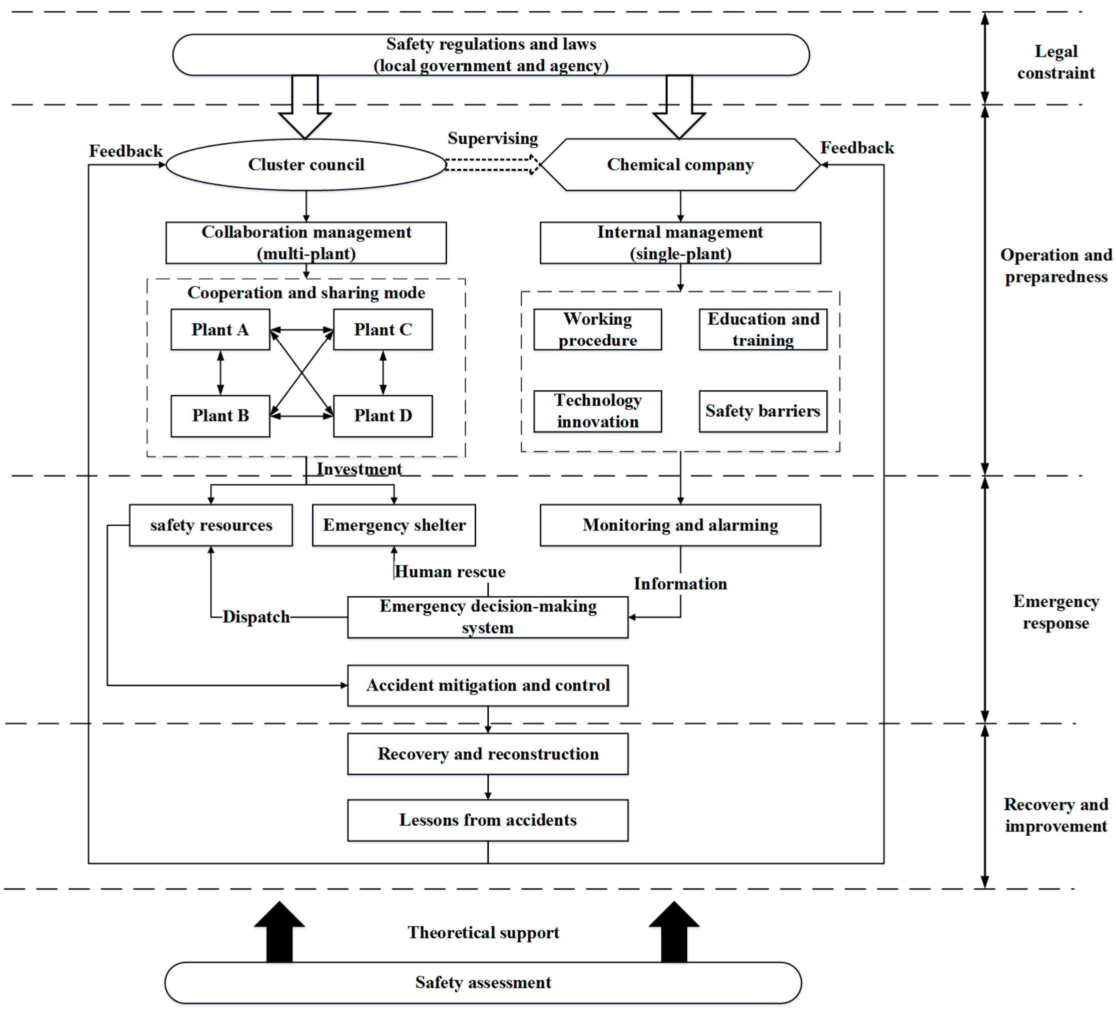

Figure 6. The integrating safety framework for CIP.

As shown in Figure 6, three topics, that is, safety management, safety assessment, and safety technology, and their involved issues, are integrated into one framework to establish a long-term safety vision for CIPs, to improve the management mechanism, to optimize collaboration, and to create synergy of emergency sources. The objective and implementation of each stage are further illustrated in detail.

(1) Legal constraint

Regulations and laws are formulated by regulatory agencies through rigorous procedures, as the basic principles to guide the implementation of safety measures and strategies. In the chemical industry, relevant regulations encompass land-use planning, compliance auditing, management of hazardous chemicals, safety training, occupational health, prevention of fire and explosion, etc. The chemical enterprise and CIP need to comply with the regulations and standards, addressing some hazardous situations that are listed in regulations, mitigating offsite consequences of chemical accidents, and protecting people from dangerous environments.

(2) Operation and preparedness

External regulations, even the most detailed and concerned rules, cannot solve all safety issues with respect to the operation of a real CIP. Therefore, internal management is necessary for a CIP, focusing safety resources on specific issues to improve its safety. As Section 3.1.2 discussed, a cluster council should be established to tackle safety issues within CIPs in a macroscopic and strategic perspective. Specifically, the operation of a cluster council can coordinate chemical companies within a CIP to follow safety strategies and rules, preventing possible accidents due to the dependent safety status of adjacent companies. The unified planning of a safety budget for dealing with external risks of a company and allocating safety resources is more cost-effective and leads to more safety. Besides, chemical companies still should take safety-related actions, such as internal working procedures, specific training and education programs for the dangerous situations, innovative safety processes and techniques, and setting prevention and protection barriers to deal with safety issues in its actual operation. In other words, safety actions of a chemical company can be concentrated on internal risks, which could facilitate proactive risk minimization. In this stage, some necessary resources and facilities for reducing the potential consequences of accidents should be prepared, in order to eliminate possible escalation effects and to improve the efficiency of emergency response.

(3) Emergency response

Monitoring and alarming system of different companies are connected to the EDS within a CIP, providing available information for the evaluation of an emergency. After an evaluation of the accident level and scope of danger and severity, intelligent EDS can provide optimal plans to guide how people evacuated to the emergency shelter, how to take measures immediately to mitigate and control accidents, and how to dispatch emergency resource with the aim to satisfy multi-plant demands in a scientific way. The accident is brought under control within the emergency process, and finally no hazard exists in the area.

(4) Recovery and improvement

Post-accident recovery needs to be done, aiming at returning to normal status and resuming production, including cleaning and treatment of the process system, repair and reconstruction of those damage installations, and indemnities for injured or deceased people. The process of the accident and emergency response should be recorded and feedbacked to managers of CIPs and chemical companies. Some major events even need to announce to the public and conduct interviews with governmental agencies. The accident causation should be corroborated and the safety strategy within CIP and chemical company should be improved to prevent similar accidents from happening once again.

In the whole process, safety assessment can provide theoretical support to safety management and emergency response, whereby vulnerable or high-risk units should be paid more attention to. The proposed framework can promote the growth of safety awareness and incorporate the individual plant safety cultures into a 'CIP safety culture' through good safety management, ultimately leading to a proactive safety strategy.

4.2. Current Research Trends

4.2.1. Hierarchical Management and Centralized Decision in CIPs

Procedural management of regulations is a conventional way to be ascertained and agreed on by the public, but as a safety baseline it cannot guarantee 'full protection' for any CIP or any chemical company. In a CIP, the possible hazards at a chemical company not only depend on the company's own safety status but also on external hazard factors due to possible cross-border accident effects. As a result, a double-layer management model, internal management of the chemical plant to prevent primary events, and collaborative management of multi-plants to avoid accident propagation is a needed safety strategy in a CIP. However, achieving full cooperation and centralized decision-making among multi-companies is challenging since it is related to organizational conundrums and communication problems. To achieve strategic cooperation about safety in a CIP, the cluster council is necessary to maintain the stability of cooperation, and cost–benefit analysis is recommended to prompt the administrators of chemical companies reaching a consensus about macro-decisions. Besides, decision-making on emergency issues in a CIP was also discussed in many studies in order to satisfy the requirement of multi-plants, mitigating possible major accidents. To establish a better safety management system in a real CIP, more strategic management and decision-making models should be explored, addressing organizational issues for CIPs.

4.2.2. Modeling Accident Evolution and Improving Assessment Approach

Safety assessment is an available and predictive tool to offer credible results for CIP safety, adopting a clear and systematic record following the assessment procedure. The vulnerability or risk calculation can provide a value in any situation and help mangers find the vulnerable installation to address the safety problems in a considered and balanced way. In the earlier studies, obtaining the probability of an accident and then evaluating its potential consequence has been the main task for QRA, which is a relatively high-level approach in safety assessment. With the in-depth investigation of domino effects related to clustering, scholars realized that hazardous events, especially in a CIP, may occur simultaneously or sequentially, so static approaches can't reflect the reality of accident propagation. Chen et al. [23] emphasized that safety assessment can be refined and improved to achieve its full potential of validity. Recently, many advanced dynamic assessment tools have been developed to model the accident evolution and accurately assess risk or vulnerability in a certain time, supporting safety management and emergency decisions. However, those dynamic tools currently are widely applied to fire-related scenarios, while temporal factors usually are ignored in explosion-related scenarios.

4.2.3. Intensifying Technical Strategy in Theoretical Perspective

Safety technology can effectively reduce risk, based on one or more prevention and protection principles, though it cannot lead to a risk-free situation. The actual functions and mitigation effects have been discussed in many studies. With the implementation of Industry 4.0, intelligent and data-driven technology emerged, making an intelligent safety system possible. Besides, there is more safety cooperation between companies or plants within a CIP, focusing on prevention and reactive issues, such as monitoring and evacuation planning. Many influential factors should be considered in the protection strategy, and therefore decision-making tools are needed to identify the best strategy for the whole CIP system to tackle systemic risks. For example, cost-effective analysis can be used to address the layout of safety barriers under a limited budget, avoiding possible accident propagation as much as possible. Moreover, many decision-making algorithms for emergency rescue have been developed to improve the efficiency of emergency processes involving multiple plants. Recently, some studies explored the combination of typical protection measures in a CIP and integrated safety technology was proposed for realizing resilient chemical industrial areas. However, past research on safety technology has been mainly concerned with prevention and protection capacities. With respect to Natech events, the monitoring system and prevention measures may be inadequate, thus raising the devastation level of a CIP.

4.3. Future Directions and Challenges

4.3.1. Optimizing Management Procedures in CIPs

Enforcing the inter-connection of multi-plants to achieve full cooperation in a CIP still is a challenge that can only be realized by optimizing the CIP organizational structure. Besides, some extreme events, like Natech events, involve various natural phenomena making them potentially devastating for CIPs. Safety education and training with multidisciplinary knowledge are also crucial for CIP safety. In this regard, a long-term oriented plan for safety management in a CIP, linked to educational and training needs, should be highlighted to create a CIP 'safety culture', guiding employees and emergency teams to behave and respond to complex incident scenarios. Overall, safety management in CIPs is a gradually evolving and progressive process, where a strategic and proactive mode should be explored better to cope with the risks.

4.3.2. Safety Assessment with Dynamic Consequence Analysis

Remarkable innovations in the field of safety assessment are the QRA and subsequent attempts of dynamic assessment. Those approaches would contribute to improving management, design, licensing, and operation related to CIPs. However, dynamic assessment poses great challenges in this domain since much of the related research has focused on probability prediction, lacking detailed analysis of physical effects. The failure of equipment and accident propagation are both complex processes that depend on structural parameters, such as equipment types and its materials, as well as the geographical parameters and meteorological factors. The temporal variations of those contributing factors may have a great impact on the accident consequence, thus dynamic consequence analysis should be explored to accurately estimate the safety status using experiments and numerical simulations.

4.3.3. Exploring Complex Evolution of Possible Accidents

Previous studies have provided an advanced insight for modeling high-level and temporal propagation of domino effects, mainly the one initiating from a single chemical accident. Moreover, they often assumed only one escalation vector existing in accident propagation. However, past accidents show that natural events can also trigger a domino accident and multiple damage factors are present and coupled in accident evolution. In other words, there are many uncertainties related to accident scenarios, for instance, failure types of installations subject to hazardous events and intensity of coupled escalation vectors, in a real domino accident. Some new concepts, like Natech domino effects and coupled-risk have been derived to describe those complex phenomena. Therefore, the evolution of accidents coupled with multiple damage factors should be further explored, which can not only improve the efficiency and accuracy of safety assessment, but also enhance the awareness of management staff or impact assessors toward potential hazardous sources.

4.3.4. Integration and Innovation of Safety Technology

The development of safety technology with the aim to prevent or mitigate undesired events, essentially, is an on-going updating and upgrading process. With the implementation of Industry 4.0, some innovations, such as wireless sensors, UAV, etc., have a promising practical application in CIPs, yet there is a lot of room for improvement. One matter for instance is the multi-variable information collected by a monitoring system for MHIs posing some difficulties to real-time warnings, how to avoid false-alarming still is a research hotspot in the future. Thus, there should be more studies in the development and industrial application of multi-objective decision-making algorithms in order to advance early warning and emergency decision. Besides, as illustrated before, the performance of combined prevention measures has been discussed in some studies. Analogously, we could also explore the integrated performance of different types of safety technologies to build a proactive and resilient safety system within CIPs. Moreover, these safety technologies have different costs and performances for different types or stages of accidents. Consequently, how to balance safety investments and potential avoiding losses may be a research issue when considering integrating safety technology.

5. Conclusions

This paper has conducted a systematic literature review of 116 documents over the past two decades, with the aim to identify the research issues and trends, as well as of prominent tools in the literature. Current research has been grouped into three categories: safety management, safety assessment, and safety technology, based on a keyword co-occurrence analysis. The presented management model related to CIPs was divided into four types: management of safety regulations, multi-plant management, single-plant management, and emergency management. Existing approaches to assess the safety status of CIPs have been classified into two groups: vulnerability assessment and risk assessment. Current technology to reduce CIP risk was categorized into three kinds: monitoring and warning, protection measures, and emergency decision-making system. For each type of different research group, this paper organized pertinent studies to investigate and classify the research features, approaches, and contributions.

Following the literature review, a safety framework for CIPs was proposed, and those nine aspects were programmed and integrated into the framework. Moreover, the research trends were identified, including hierarchical management and centralized decisions in CIPs, modeling accident evolution and improving assessment approach, and intensifying technical strategy in theoretical perspective. Corresponding methods or tools have contributed a lot to the safety and sustainability development of CIPs. Nonetheless, challenges still exist with respect to the in-depth research and new risks, such as optimizing management procedures in CIPs, exploring complex evolution of possible accidents, and integration and innovation of safety technology. Further studies are needed to deal with CIP risks in an intelligent and systemic way.

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