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State-of-the-Art

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Multi-hazard risk assessment in process industries: State-of-the-Art

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ABSTRACT

Multi-hazard accidents in process industries, which can cause more severe consequences compared to individual accidents, have gained growing attention from administrators and scholars in recent years. With the development of process industries and the expansion of the urban area, high-risk zones may emerge in densely populated areas. Accurate risk assessment of the multi-hazard accidents in process industries is essential for protecting properties, human life, and the environment. This study reviews past studies on the risk assessment of three types of multi-hazard accidents in process industries: Natech events, domino effects, and concurrent hazards. The development trends of risk assessment of multi-hazard accidents are analyzed and the research gasps of past research are identified. Based on the identified gaps in previous research, future perspectives on multi-hazard research in process industries are discussed. To improve the assessment methods for multi-hazard risks, more advanced basic models and applicative risk analysis methods are required. Considering multi-hazard interactions and other factors are also important for process plants against multi hazards. This study can potentially contribute to developing better risk assessment models of multi-hazard accidents and therefore safer and resilient process industries.

1. Introduction

The term “multi-hazard” has been widely used in government documents and academic literature. It is defined by United Nations Office for Disaster Risk Reduction (UNDRR) as “an approach that considers more than one hazard in a given place and the interrelations between these hazards, including their simultaneous or cumulative occurrence and their potential interactions” (UNDRR, 2015). The concept of multi-hazard is closely related to natural hazards in many documents such as the United Nations’ Agenda 21 for sustainable development (United Nations, 1992), Hyogo Framework for Action (UNDRR, 2005), and Sendai Framework for Disaster Risk Reduction (UNDRR, 2015). Nevertheless, with the development of process industries, multi-hazard risks have also received attention in the research on technological accidents (Chen et al., 2019; Qin et al., 2020).

Due to the flammable, explosive and toxic properties of hazardous chemicals, fires, explosions, and toxic releases are three major accidents in process industries (Papadakis and Amendola, 1997). The research on multi-hazard accidents in process industries considers the causality, concurrence and interaction of the major accidents and natural hazards, which can be divided into three categories: Natech events, domino effects, and concurrent hazards (Wang et al., 2020). In this study, the three types of multi-hazard accidents focus on different accident phenomena respectively. Natech events refer to “natural hazard triggering technological accidents” (Cruz et al., 2006). Domino effects refer to the phenomenon in which one technological accident causes one or more technological accidents (Abdolhamidzadeh et al., 2011). Concurrent hazards refer to simultaneous hazards, which can be the same type or different types of natural hazards or technological accidents, and the interactions between them (Cutter, 2018).

Due to climate change and industrial development, there is an increasing trend in the frequency of multi-hazard accidents in process industries (Cruz and Suarez-Paba, 2019; Ricci et al., 2021). Several severe multi-hazard accidents happened in the last decade. For instance, the Great East Japan Earthquake in 2011 triggered typical Natech events, producing significant impacts on people and the environment (Krausmann and Cruz, 2013). The explosion accidents that occurred in Tianjin, China, 2015 (Fu et al., 2016), and Beirut, Lebanon, 2020 (Valsamos et al., 2021), were both typical domino effects triggered by uncontrollable fire accidents. Besides, the damage of the multi-hazard

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accidents in process industries is considered to be more severe than single accidents, because multi-hazard accidents usually involve multiple installations and can affect larger areas (Gehl and D'Ayala, 2016). Another reason is that the interactions in multi-hazard accidents (e.g., synergistic effects and coupling effects) can amplify the consequences of accidents and result in unanticipated damages (He and Weng, 2020a).

Besides, industrial development may make the consequences of multi-hazard accidents more severe due to the adverse effects of large-scale industrial agglomeration areas and centralized industrial clusters (Reniers et al., 2009; Zhang and Chen, 2013). Moreover, with the urbanization in developing countries such as China and India, the industrial development may result in the emergence of high-risk zones in densely populated areas (Reniers, 2010). To overcome these challenges, multi-hazard risk assessment and management tools are necessary for accident prevention and land-use planning in urban and industrial areas.

There is an urgent need to pay attention to the multi-hazard risk assessment in process industries, which is the consensus of administrators and scholars worldwide (Amin et al., 2019; Zhang and Glezakou, 2021). In the past few decades, public policies and academic research have paid attention to this issue and made it a hot topic. However, the multi-hazard risk is still an emerging concept and thus some gaps remain in government documents and academic literature. This paper aims to review the cutting-edge research results of the multi-hazard risk assessment in process industries and identify the gaps that may be addressed in future research. Moreover, based on the identified gaps of previous research, this paper proposes perspectives for future research on multi-hazard risks in process industries.

2. Multi-hazard risk assessment methods

In recent decades, the publications of several reference books on process safety have given scholars a clear understanding of the mechanisms, frequency, and consequences of major accidents: fires, explosions, and toxic releases. The "color books" published by the Netherlands Organization of Applied Scientific Research (TNO) systematically introduced the damage analysis, probability determination, and quantitative risk assessment (QRA) methods for process industries (TNO, 1992; TNO, 1997; TNO, 1999; TNO, 2005). The U.S. Center for Chemical Process Safety (CCPS) published the guidance for chemical process QRA and updated the contents according to the development of the process industry (CCPS, 2000; CCPS, 2007). The reference book published by Assael and Kakosimos (2010) concentrated on the effects and consequences analysis and reviewed the risk analysis methods for major accidents. More recently, the Society of Fire Protection Engineers (SFPE) published a handbook, focusing on fire-induced major accidents (SFPE, 2016).

Compared to major accidents, the research on multi-hazard accidents in process industries is relatively preliminary (He and Weng, 2020b). However, according to a survey of 207 accidents, 55% of process industry accidents have multi-hazard characteristics (Zhang and Chen, 2013). There is still plenty of scope for research on the risks of multi-hazard accidents in process industries. In the following sub-sections, multi-hazard risk assessment methods for process industries are reviewed from three aspects: Natech events, domino effects, and concurrent hazards. The focuses of the research on the different types of multi-hazard accidents are shown in Fig. 1. Natech events and domino effects always focus on the causal (triggering) relationship of different hazards while concurrent hazards highlight the interactions of concurrent hazards (with or without causal relationships).

2.1. Natech event

The concept of Natech events was first proposed by Showalter and Myers (1994) and quickly gained attention from governments and scholars. Several Natech event prevention projects have been launched in recent years. HAZUS was launched by the U.S. Federal Emergency Management Agency (FEMA) and has been applied worldwide (FEMA, 1997; Remo and Pinter, 2012). Project ARMONIA was launched by the European Commission and aimed to apply multi-hazard mapping to assess the physical, social, economic, and functional damage of the natural hazards (European Commission, 2004). Other global projects were Natech I and Natech II projects, initiated by the Organization for Economic Cooperation and Development (Krausmann and Baranzini, 2012).

With the inspiration of the prevention projects, scholars have conducted academic research on risk assessment methods for Natech events, which has experienced a development process from qualitative to semi-quantitative to quantitative (Mesa-Gómez et al., 2020). Salzano et al. (2013) developed a qualitative methodology for risk assessment of the Natech events based on an analytical hierarchy process method. A Bow-tie diagram (El Hajj et al., 2015) was also applied to conduct the qualitative risk assessment considering natural hazards and vulnerability. A well-known semi-quantitative risk assessment method named RAPID-N (Girgin and Krausmann, 2012, 2013) aimed to conduct quick assessment and mapping of the Natech risks. In terms of the quantitative risk assessment, Bayesian network (BN) (Khakzad and Van Gelder, 2018) and Monte Carlo simulation (MCS) (Alessandri et al., 2018) were used to calculate the probabilities of Natech events and their escalations. Additionally, a geographic information system was a tool widely used in data analysis, mapping, and risk assessment of the Natech events (Soto and Renard, 2015; Ancione et al., 2016).

Most of the studies on Natech events focused on specific types of natural hazards. Lightning, floods, and earthquake gained most of the attention in previous studies on the Natech events (Mesa-Gómez et al., 2020). Misuri et al. (2020) presented a QRA method for lightning-triggered Natech events based on a probit approach and a

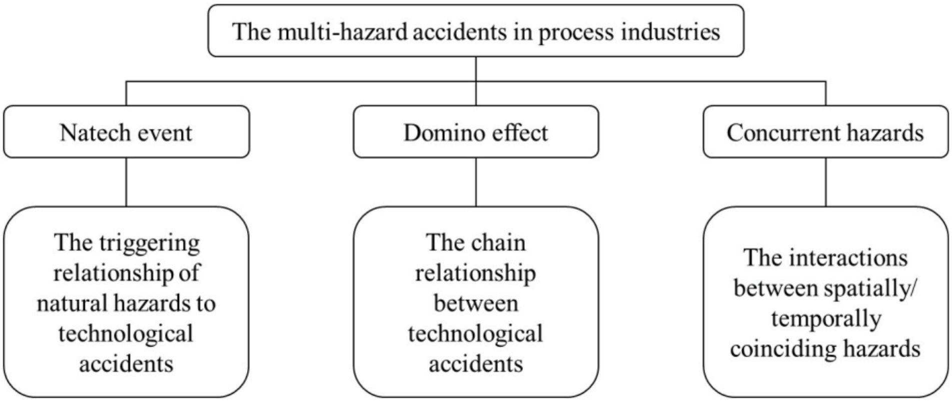

Fig. 1. The focuses of the research on the different types of multi-hazard accidents in process industries.

combinatorial analysis. Antonioni et al. (2015) proposed a QRA method for flood-triggered Natech events using new equipment vulnerability models. The Natech events initiated by earthquakes were also studied by Bursi et al. (2018) using a performance-based earthquake engineering procedure. The QRA models and methods for these three natural hazards account for 54% of the publications on quantitative Natech event research (Mesa-Gómez et al., 2020), as shown in Fig. 2.

Besides, review papers also provided an overview of the research on Natech events. Cruz (Cruz et al., 2004; Cruz and Okada, 2008; Cruz, 2012) published a series of review papers to show the development of the Natech event research in recent decades. Mesa-Gómez (Mesa-Gómez et al., 2020, 2021) reviewed the risk assessment methods for Natech events and presented recommendations for future research. A reference book published by Krausmann et al. (2016) systematically reviewed the risk reduction methods for Natech events. Other review papers (e.g., published by Steinberg et al. (2008), Ricci et al. (2021), and Misuri and Cozzani (2021)) also provided understandings of the Natech event research.

2.2. Domino effect

Domino effects were first systematically studied by Bagster and Pitblado (1991). As the most common multi-hazard accident in process industries, domino effects have also driven governments to formulate accident prevention strategies (He and Weng, 2020b). The European Commission issued the Seveso Directive in which the assessment of domino hazards was required in process plants (OJEU, 1982). Subsequently, Seveso-II Directive and Seveso-III Directive were issued to emphasize the domino risks in process industries (OJEU, 1996; OJEU, 2012). The CCPS recommended that multiple safety barriers and layers should be established in process plants to prevent domino effects (CCPS, 2019).

Similarly, risk assessment of the domino effects also has gone through a development process from vague to precise (Swuste et al., 2019). Matrix-based (Ni et al., 2010) and index-based methods (Khan and Abbasi, 1998a) were the representatives of qualitative and semi-quantitative risk assessment methods. Other methods such as HAZOP analysis (Khan and Abbasi, 1997), layer of protection analysis (Markowski and Kotynia, 2011), and "What-If" analysis (Assael and Kakosimos, 2010) were also widely used as semi-quantitative hazard identification and risk assessment methods.

With an in-depth understanding of the domino process, various QRA methods for domino effects have been proposed since 2000. Khan proposed maximum credible accident analysis and developed a QRA software DOMIFFECT, considering the consequence and frequency of the domino effects in risk assessment (Khan and Abbasi, 1998b). Cozzani et al. (2005) proposed a QRA method for domino effects by using probit models in consequence, damage, and escalation assessment. In recent years, Khakzad (Khakzad et al., 2011, 2013) and Abdolhamidzadeh et al. (2010) focused on calculating the likelihood of domino escalation process and proposed BN-based and MCS-based QRA methods respectively. More methods such as event tree analysis (Chen F. et al., 2020), fault tree analysis (Khan and Abbasi, 1999), graph theory metrics (Khakzad et al., 2017a; Chen et al., 2018), game theory (Zhang et al., 2018), and Petri-net (Zhou and Reniers, 2018a), expanded the application of mathematical and physical models in the QRA methods for domino effects. Moreover, the application of fuzzy set theory brought out several QRA methods for the domino effects, such as fuzzy Bayesian network (Guo et al., 2021), fuzzy Petri-net (Zhou and Reniers, 2017), and Choquet integral (He and Weng, 2021).

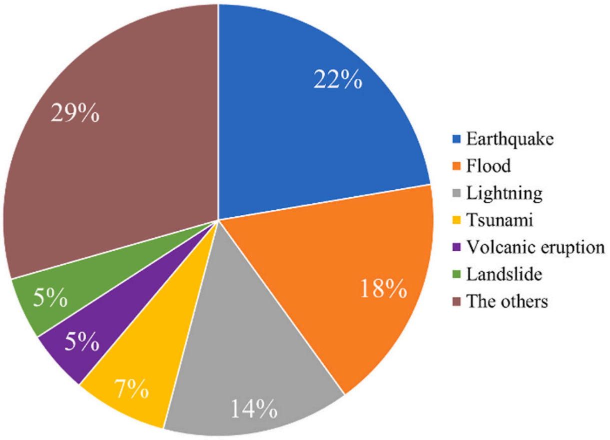

Fig. 2. The ratios of different types of natural hazards in the quantitative Natech event research (date from Mesa-Gómez et al., 2020).

With the development of domino effect research, the development trend of risk assessment methods becomes clear. Quantitative, dynamic, and realistic risk assessment can be regarded as three development trends. Subjective evaluation has also become a development trend for improving risk assessment methods with the application of fuzzy set theory. The development trends are shown in Fig. 3.

For a better understanding of the development of the risk assessment methods for domino effects, scholars published several reference books and review papers. The reference book published by Reniers and Cozzani (2013) systematically reviewed the modeling, prevention, and managing of domino effects. Khan et al. (2015) elaborately illustrated the development of the risk assessment methods for domino effects from qualitative to quantitative. Necci et al. (2015) and Chen C. et al. (2020) presented the state-of-the-art of the domino effect risk assessment and pointed out the gaps in previous research. Li et al. (2017) conducted a bibliometric analysis on the publications and summarized the hot topics on domino effects.

2.3. Concurrent hazards

Concurrent hazards refer to the concurrence of the same type or different types of technological accidents or natural hazards. Fig. 4 explains the concept and classification of concurrent hazards. Different from Natech events and domino effects, the past research on concurrent hazards focuses more on the interactions between hazards rather than the hazard itself. The interactions not only exist in concurrent natural hazards and technological accidents internally but also externally between the natural hazards and technological accidents.

The classification of the interactions in concurrent hazards can refer to the combined effects of the impact of chemicals on human bodies proposed by the European Food Safety Authority (EFSA, 2013): linear superposition, magnification, and reduction. Similarly, Wang (Wang et al., 2020) divided the interactions into three categories: non-influential hazards, mutually exclusive hazards, and mutually amplified hazards. A collaborative group in the U.K. conducted in-depth research on the concurrent hazard relationships and divided them into three categories: increasing/decreasing the probability, coinciding spatially/temporally, exacerbate/alleviate (Gill and Malamud, 2014).

Except for the classification, due to the complexity and uncertainty of the interactions between hazards, other research results on the concurrent hazards are preliminary, intuitively reflected in the application of terminology. Table 1 non-inclusively shows the terms used by scholars to describe the interactions.

The interactions in concurrent natural hazards have been studied by many scholars. Gill and Malamud (2014) identified 90 possible interactions between 21 different natural hazards. More specifically, Huggel et al. (2004) investigated the synergic effects of ice avalanches and mobilized periglacial debris on lake outbursts. Other scholars revealed that the building covered by snow or volcanic ash was more vulnerable in an earthquake (Lee and Rosowsky, 2006; Zuccaro et al., 2008). Although most studies on concurrent natural hazards did not involve technological accidents, the concepts and methods in these

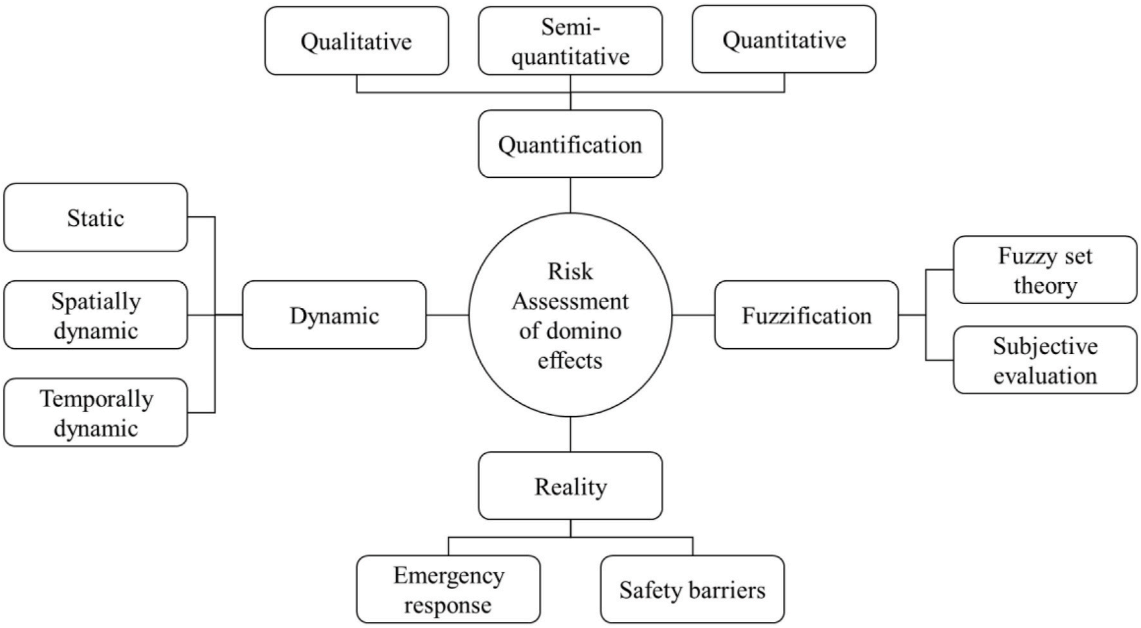

Fig. 3. The tendency of development of the risk assessment methods for domino effects.

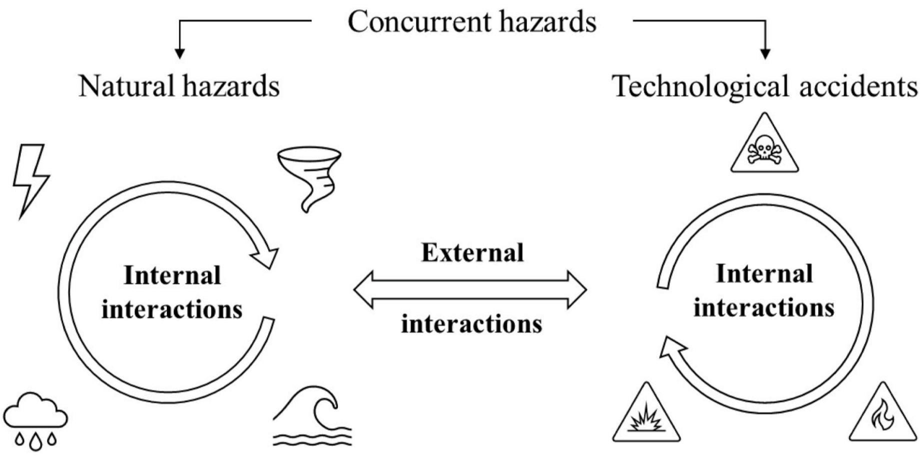

Fig. 4. The internal and external interactions in concurrent hazards.

studies can be used for reference in process safety research.

Compared to the natural hazards, studies focusing on the interactions in concurrent technological accidents are few. He and Weng (2020a) proposed the coupling effects and tried to reveal the mechanisms of the interactions in the physical effects of technological accidents. Landucci et al. (2016) and Chen et al. (2018) focused on the synergistic effects on emergency response. Ding et al. investigated the synergistic effects by evaluating the collaborative interactions of concurrent technological accidents. The vulnerability of installations was also studied as one kind of interaction in concurrent technological hazards (Khakzad et al., 2016).

The interactions between concurrent technological accidents and natural hazards are usually neglected in the multi-hazard risk assessment in process industries. In a limited number of references, wind was considered to be an important environmental factor that could interact with technological accidents, such as fires (Rossa and Fernandes, 2018; Węgrzyński and Lipecki, 2018) and toxic releases (Qian et al., 2019). Howes et al. (2013) proposed that the toxic releases in a flood-triggered Natech event would contaminate the flood waters and pose impacts to people and the environment. Necci et al. (2018) proposed that the emergency response in Natech events could be hampered due to the concurrence of technological accidents and natural hazards.

3. Future perspectives

Although a lot of effort has been made in the research on multi-hazard risks in process industries, gaps still exist in the previous studies. This section aims to propose perspectives on future research based on the gaps in previous research on the multi-hazard risk assessment in process industries. The development trend of the research inclines to the following aspects: advanced basic models, applicative risk assessment methods, determination of the interactions, and consideration of other factors.

3.1. *Advanced basic models*

Consequence analysis models, escalation probability models, and damage analysis models are the basic models in the risk assessment of process accidents (Cozzani et al., 2005). Although the research on process accidents is being improved, the development of the research on

Table 1

The terms used by scholars to describe the interactions in concurrent hazards.

Terms	Scholars	Definitions
Coinciding hazards	European Commission (2011)	The cumulative impact of all of the various impacts occurring at the same time or shortly following each other.
Synergic effect	Tarvainen et al. (2006), Omidvar and Kivi (2016)	One hazard is a cause of influences on other hazards.
Synergistic effect	Zhou and Reniers (2018b), Chen et al. (2018), Ding et al. (2020)	The collaboration of concurrent primary and secondary accidents to trigger another accident in a tertiary unit and so forth.
Compound hazard	Alexander and Fairbridge (1999)	Several elements acting together above their respective damage threshold.
Combined effects	EFSA (2013)	Cumulative risk caused by the exposure to multiple hazards.
Superimposed effect	Chen et al. (2018)	The influence of the current hazard can be superimposed on another hazard.
Cumulative effect	Stelzenmüller et al. (2018), Stelzenmüller et al. (2020)	The combined effects of human activities and natural processes on the environment.
Joint effect	Berrington de González and Cox (2005), Kim et al. (2017)	Additive and multiplicative effects of two risk factors on a binary outcome.
Coupling effect	Kappes et al. (2012), He and Weng (2020a)	Hazards influence each other, resulting in amplified/reduced consequences.

advanced basic models is relatively stagnant. For instance, the point source model and solid flame model of fires, TNT-equivalent model of explosions, and Gaussian diffusion model of toxic releases are the mainstream consequence analysis models for the risk assessment of process accidents (Casal, 2017). These models are simplified and empirical which cannot inclusively consider the multi-factor influences in multi-hazard scenarios. Methods that can consider the propagation process of the accidents in actual scenarios are expected in the consequence analysis of process accidents, like computational fluid dynamics (Giannissi et al., 2013; Sun and Guo, 2013). In terms of the escalation probability and damage analysis models, previous research is relatively preliminary, such as the models of fragment impact and toxic damage. Although tentative research has been conducted (Sun et al., 2015, 2016), corresponding results still lack practicality in risk assessment.

The same gap exists in the research on Natech events. According to a dataset of 9100 Natech events, meteorological events were found to account for 86% of the case of Natech scenarios, such as storms and extreme temperature (Ricci et al., 2021). However, previous research and established models of Natech events mainly focused on earthquakes and floods (Mesa-Gómez et al., 2020). Moreover, the establishments of Natech event models also are complex and uncertain, which is one of the challenges that restrict the research on Natech event risk assessment. To overcome these challenges, inclusive and precise basic models of Natech events are needed, including the models of different types of natural hazards and the models of escalation processes in Natech scenarios. In recent years, scholars have made progress in studying the advanced basic models of Natech events, especially the models of escalation processes, such as the damage analysis of the installations in floods (Zeng et al., 2021), storms (Bernier et al., 2019), and earthquakes (Huang et al., 2020).

3.2. Applicative risk assessment methods

One of the challenges in multi-hazard risk assessment for process industries is the gap between academic research and practical application. The causes of this gap are various. The first is the practicability of the risk assessment methods. Some precise methods, such as the BN-based and MCS-based QRA methods, can accurately simulate the multi-hazard process but are time-consuming when dealing with complex multi-hazard scenarios (Chen et al., 2018). On the contrary, other methods, such as the matrix-based and index-based methods, aiming at reducing the complexity of calculation, will introduce uncertainty into the risk assessment when adopting the simplifications (Khan et al., 2015). To overcome this limitation, risk assessment methods that can balance the accuracy and computing capacity are expected.

Second, the multi-hazard risk assessment methods for process industries are developing from static analysis to dynamic analysis. The spatial-temporal evolution of multi-hazard scenarios is one of the characteristics of the Natech and domino events, which was often neglected in the previous risk assessment methods (Ding et al., 2020). Recently, a dynamic BN-based method was presented to simulate the propagation of multi-hazard processes (Khakzad et al., 2017b). The MCS-based method was optimized to be applicable in the dynamic risk assessment (Rad et al., 2014). Although some studies have been conducted aiming at filling this gap, more attention is still needed.

A paradigm shift in the multi-hazard risk assessment of process industries is needed. One of the alternatives is applying the subjective evaluations from experienced experts when it is challenged to improve the accuracy of the risk assessment methods. Fuzzy theory has been widely used in the studies on finance and information science (Wang, 2016; Havens and Anderson, 2019), which is also appropriate to handle the uncertain risk assessment in process industries. The development of multi-hazard risk assessment methods based on the fuzzy theory is worth looking forward to.

3.3. Determination of the interactions

As shown in Table 1, the multi-hazard interactions have been defined by multiple terms. Each term has a unique definition and its own focus. The application of various terms indicates that the interactions between hazards are a hot topic in multi-hazard research. However, it also shows that the previous research is unsystematic. Unifying the terminology is one of the urgent goals for the research on multi-hazard interactions. It is not only conducive to improving the sustainability of the research but also conducive to the communication of the research results. The focus of the research on multi-hazard interactions also requires discussion and consensus to improve the efficiency of research.

Moreover, most of the terms in Table 1 focus on linear interactions between hazards, such as linear superposition or collaboration. Few terms describe the mechanisms and principles of the multi-hazard interactions, which are mostly recognized to be nonlinear (Kameshwar and Padgett, 2014). The determination of the nonlinear interactions in concurrent hazards can improve the accuracy of risk assessment. Future research can classify the multi-hazard interactions in more detail, and conduct mechanism analysis from specific aspects, such as the vulnerability of installations and human bodies, and the emergency response.

Finally, the multi-hazard risks in the process industry were divided into different categories and studied separately in most of the references. The classification of multi-hazard risks makes the multi-hazard research more specific, but meanwhile, it also brings barriers to the cross-category multi-hazard research. It is expected that inclusive multi-hazard risk assessment methods can be presented, such as the research on domino effects which considers the interactions of concurrent technological accidents, and the research on Natech events which considers the interactions of concurrent natural hazards and technological accidents. Similar attempts have been made by some scholars (Cozzani et al., 2014; Misuri et al., 2020). It is also expected that an inclusive system for cross-category multi-hazard risk assessment research can be developed in the future such as database, software, or experimental platforms.

3.4. Consideration of other factors

Besides improving the risk assessment methods, it is also important to consider the influences of other factors in the multi-hazard research in process industries. Risk assessment methods will encounter many challenges in practical applications, one of which is on-site cooperation and information exchange. The contradiction between financial benefits and safety investment in process industries makes the risk assessment methods that have high requirements for cooperation and information collection lack of practicability (Reniers et al., 2012; Swuste et al., 2019; Wu et al., 2020). Accurate and concise risk assessment methods are expected by both administrators and process industry companies. The introduction of subjective evaluation and the application of fuzzy theory is one of the new ideas for improving the risk assessment methods.

Most of the risk assessment methods are based on individual risk and social risk, which focus on the potential harm to human bodies from multi-hazard accidents in process industries. However, with the recognition of the importance of environmental protection, especially after the formulation of the framework of the Global Pact for the Environment (United Nations, 2017), flora, fauna, and environment are the factors that have gained growing concern in the risk assessment of process industries. Moreover, with the overlap of industrial and urban areas, economic loss and infrastructure damage should also be considered in the risk assessment. The diversification of risk criteria is one of the future goals for multi-hazard research in process industries.

4. Concluding remarks

With the recognition of the complexity and uncertainty of the triggering factors and propagation processes of the multi-hazard accidents in process industries, growing attention has been paid to the research of multi-hazard risk assessment and management. Nevertheless, as a new topic on process safety raised in recent decades, the multi-hazard research in process industries is relatively in a preliminary stage. To provide researchers and other readers with a general image of the existing knowledge on multi-hazard risk assessment in process industries, this paper reviews previous research on this topic, identifies the gaps in the past research, and provides perspectives on future research.

Compared to the research on the major accidents in process industries, the multi-hazard research is relatively few and preliminary. The research objects of the risk assessment of Natech events are found to be uneven and concentrated on earthquakes, floods, and lightning; The development trends of the risk assessment methods for domino effects are classified into four categories: quantification, dynamic, reality, and fuzzification; The research on concurrent hazards, which mainly focuses on the interactions between hazards, is found to be preliminary and unsystematic.

Based on the identified gaps in previous research, four future needs of the multi-hazard research in process industries are discussed. First, more advanced basic models of the technological accidents and natural hazards are expected, such as the models of fragment impact and toxic damage. The computational fluid dynamics methods suitable for multi-hazard analysis are also expected. Second, the risk assessment methods are expected to find a balance between accuracy and complexity. Precise risk assessment methods can be time-consuming at the same time. Practical risk assessment methods can be the combination of precise simulations and subjective evaluations. Third, the research on multi-hazard interactions needs to be more systematic and go deeper into the analysis of mechanisms and principles. The terms and concepts of multi-hazard interactions should be unified. The research on nonlinear multi-hazard interactions should attract more attention. Finally, risk assessment methods need to consider more factors. The practicability of risk assessment methods can be questionable in actual process industries. The presentation of new risk assessment methods requires on-site investigation in advance.

The multi-hazard risk is an important research topic in process safety research. There are extensive research results of multi-hazard accidents. Providing a detailed and systematic review of the research on each type of multi-hazard risk is difficult in a short paper. Therefore, this paper tries to provide an overview of the research on multi-hazard risk assessment in process industries and provides perspectives on future research. This work can provide insights for future research on multi-hazard risk assessment and contribute to the safety and sustainability of process industries.

Author contribution statement

Zhichao He: literature searching, Writing – original draft & review. Chao Chen: Resource, Writing – review & editing. Wenguo Weng, Conceptualization, Resource, Investigation, Writing – review & editing, Project administration, Funding acquisition.

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Declaration of competing interest

The authors have no competing interests to declare.

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References

Abdolhamidzadeh, B., Abbasi, T., Rashtchian, D., Abbasi, S.A., 2010. A new method for assessing domino effect in chemical process industry. J. Hazard Mater. 182, 416–426. https://doi.org/10.1016/j.jhazmat.2010.06.049.

Abdolhamidzadeh, B., Abbasi, T., Rashtchian, D., Abbasi, S.A., 2011. Domino effect in process-industry accidents–an inventory of past events and identification of some patterns. J. Loss Prev. Process. Ind. 24 (5), 575–593. https://doi.org/10.1016/j.jlp.2010.06.013.

Alessandri, S., Caputo, A.C., Corritore, D., Giannini, R., Paolacci, F., Phan, H.N., 2018. Probabilistic risk analysis of process plants under seismic loading based on Monte Carlo simulations. J. Loss Prev. Process. Ind. 53, 136–148. https://doi.org/10.1016/j.jlp.2017.12.013.

Alexander, D.E., Fairbridge, R.W., 1999. Encyclopedia of Environmental Science. Springer, Dordrecht.

Amin, M.T., Khan, F., Amyotte, P., 2019. A bibliometric review of process safety and risk analysis. Process Saf. Environ. Protect. 126, 366–381. https://doi.org/10.1016/j.psep.2019.04.015.

Ancione, G., Salzano, E., Maschio, G., Milazzo, M.F., 2016. A GIS-based tool for the management of industrial accidents triggered by volcanic ash fallouts. J. Risk Res. 19 (2), 212–232. https://doi.org/10.1080/13669877.2014.961515.

Antonioni, G., Landucci, G., Necci, A., Gheorghiu, D., Cozzani, V., 2015. Quantitative assessment of risk due to NaTech scenarios caused by floods. Reliab. Eng. Syst. Saf. 142, 334–345. https://doi.org/10.1016/j.ress.2015.05.020.

Assael, M.J., Kakosimos, K.E., 2010. Fires, Explosions, and Toxic Gas Dispersions: Effects Calculation and Risk Analysis. CRC Press, Boca Raton.

Bagster, D.F., Pitblado, R.M., 1991. The estimation of domino incident frequencies–an approach. Trans. IChemE. 69, 195–199.

Bernier, C., Gidaris, I., Balomenos, G.P., Padgett, J.E., 2019. Assessing the accessibility of petrochemical facilities during storm surge events. Reliab. Eng. Syst. Saf. 188, 155–167. https://doi.org/10.1016/j.ress.2019.03.021.

Berrington de González, A., Cox, D.R., 2005. Additive and multiplicative models for the joint effect of two risk factors. Biostatistics 6 (1), 1–9. https://doi.org/10.1093/biostatistics/kxh024.

Bursi, O.S., di Filippo, R., La Salandra, V., Pedot, M., Reza, M.S., 2018. Probabilistic seismic analysis of an LNG subplant. J. Loss Prev. Process. Ind. 53, 45–60. https://doi.org/10.1016/j.jlp.2017.10.009.

Casal, J., 2017. Evaluation of the Effects and Consequences of Major Accidents in Industrial Plants. Elsevier, Amsterdam.

Centre for Chemical Process Safety (CCPS), 2000. Guidelines for Chemical Process Quantitative Risk Analysis, second ed. American Institute of Chemical Engineers, New York.

Centre for Chemical Process Safety (CCPS), 2007. Guidelines for Risk Based Process Safety. Wiley, New York.

Centre for Chemical Process Safety (CCPS), 2019. Guidelines for Investigating Process Safety Incidents, third ed. Wiley, New York.

Chen, C., Reniers, G., Zhang, L., 2018. An innovative methodology for quickly modeling the spatial-temporal evolution of domino accidents triggered by fire. J. Loss Prev. Process. Ind. 54, 312–324. https://doi.org/10.1016/j.jlp.2018.04.012.

Chen, G., Huang, K., Zou, M., Yang, Y., Dong, H., 2019. A methodology for quantitative vulnerability assessment of coupled multi-hazard in Chemical Industrial Park. J. Loss Prev. Process. Ind. 58, 30–41. https://doi.org/10.1016/j.jlp.2019.01.008.

Chen, C., Reniers, G., Khakzad, N., 2020. A thorough classification and discussion of approaches for modeling and managing domino effects in the process industries. Saf. Sci. 125, 104618. https://doi.org/10.1016/j.ssci.2020.104618.

Chen, F., Wang, C., Wang, J., Zhi, Y., Wang, Z., 2020. Risk assessment of chemical process considering dynamic probability of near misses based on Bayesian theory and event tree analysis. J. Loss Prev. Process. Ind. 68, 104280. https://doi.org/10.1016/j.jlp.2020.104280.

Cozzani, V., Gubinelli, G., Antonioni, G., Spadoni, G., Zanelli, S., 2005. The assessment of risk caused by domino effect in quantitative area risk analysis. J. Hazard Mater. 127, 14–30. https://doi.org/10.1016/j.jhazmat.2005.07.003.

Cozzani, V., Antonioni, G., Landucci, G., Tugnoli, A., Bonvicini, S., Spadoni, G., 2014. Quantitative assessment of domino and NaTech scenarios in complex industrial areas. J. Loss Prev. Process. Ind. 28, 10–22. https://doi.org/10.1016/j.jlp.2013.07.009.

Cruz, A.M., 2012. Challenges in NaTech risk reduction. Rev. Ing. (37), 79–86. https://doi.org/10.16924/revinge.37.12.

Cruz, A.M., Okada, N., 2008. Methodology for preliminary assessment of Natech risk in urban areas. Nat. Hazards 46 (2), 199–220. https://doi.org/10.1007/s11069-007-9207-1.

Cruz, A.M., Suarez-Paba, M.C., 2019. Advances in Natech research: an overview. Prog. Disast. Sci. 1, 100013. https://doi.org/10.1016/j.pdisas.2019.100013.

Cruz, A.M., Steinberg, L.J., Vetere Arellano, A.L., Nordvik, J.P., Pisano, F., 2004. State of the Art in Natech Risk Management. European Commission Joint Research Centre, Brussels.

Cruz, A.M., Steinberg, L.J., Vetere-Arellano, A.L., 2006. Emerging issues for natech disaster risk management in Europe. J. Risk Res. 9 (5), 483–501. https://doi.org/10.1080/13669870600717657.

Cutter, S.L., 2018. Compound, cascading, or complex disasters: what's in a name? Environ. Sci. Policy Sustain. Dev. 60 (6), 16–25. https://doi.org/10.1080/00139157.2018.1517518.

Ding, L., Khan, F., Ji, J., 2020. A novel approach for domino effects modeling and risk analysis based on synergistic effect and accident evidence. Reliab. Eng. Syst. Saf. 203, 107109. https://doi.org/10.1016/j.ress.2020.107109.

European Food Safety Authority (EFSA), 2013. International frameworks dealing with human risk assessment of combined exposure to multiple chemicals. Efsa J. 11 (7) https://doi.org/10.2903/j.efsa.2013.3313.

El Hajj, C., Piatyszek, E., Tardy, A., Laforest, V., 2015. Development of generic bow-tie diagrams of accidental scenarios triggered by flooding of industrial facilities (Natech). J. Loss Prev. Process. Ind. 36, 72–83. https://doi.org/10.1016/j.jlp.2015.05.003.

European Commission, 2004. Applied Multi Risk Mapping of Natural Hazards for Impact Assessment. https://cordis.europa.eu/project/id/511208. (Accessed 16 December 2011). accessed.

European Commission, 2011. Risk Assessment and Mapping Guidelines for Disaster Management. European Union, Brussels.

Federal Emergency Management Agency (FEMA), 1997. Hazus. https://www.fema.gov/flood-maps/products-tools/hazus. (Accessed 16 February 2021) accessed.

Fu, G., Wang, J., Yan, M., 2016. Anatomy of Tianjin port fire and explosion: process and causes. Process Saf. Prog. 35 (3), 216–220. https://doi.org/10.1002/prs.11837.

Gehl, P., D'Ayala, D., 2016. Development of Bayesian Networks for the multi-hazard fragility assessment of bridge systems. Struct. Saf. 60, 37–46. https://doi.org/10.1016/j.strusafe.2016.01.006.

Giannissi, S.G., Venetsanos, A.G., Markatos, N., Bartzis, J.G., 2013. Numerical simulation of LNG dispersion under two-phase release conditions. J. Loss Prev. Process. Ind. 26 (1), 245–254. https://doi.org/10.1016/j.jlp.2012.11.010.

Gill, J.C., Malamud, B.D., 2014. Reviewing and visualizing the interactions of natural hazards. Rev. Geophys. 52 (4), 680–722. https://doi.org/10.1002/2013RG000445.

Girgin, S., Krausmann, E., 2012. Rapid Natech Risk assessment and mapping tool for earthquakes. Rapid-N. Chem. Eng. Trans. 26, 93–98. https://doi.org/10.3303/CET1226016.

Girgin, S., Krausmann, E., 2013. RAPID-N: rapid Natech risk assessment and mapping framework. J. Loss Prev. Process. 26 (6), 949–960. https://doi.org/10.1016/j.jlp.2013.10.004.

Guo, X., Ji, J., Khan, F., Ding, L., Yang, Y., 2021. Fuzzy Bayesian network based on an improved similarity aggregation method for risk assessment of storage tank accident. Process Saf. Environ. Protect. 149, 817–830. https://doi.org/10.1016/j.psep.2021.03.017.

Havens, T.C., Anderson, D.T., 2019. Machine learning of choquet integral regression with respect to a bounded capacity (or non-monotonic fuzzy measure). In: 2019 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE), pp. 1–6. https://doi.org/10.1109/FUZZ-IEEE.2019.8858835.

He, Z., Weng, W., 2020a. Synergic effects in the assessment of multi-hazard coupling disasters: fires, explosions, and toxicant leaks. J. Hazard Mater. 388, 121813. https://doi.org/10.1016/j.jhazmat.2019.121813.

He, Z., Weng, W., 2020b. A dynamic and simulation-based method for quantitative risk assessment of the domino accident in chemical industry. Process Saf. Environ. Protect. 144, 79–92. https://doi.org/10.1016/j.psep.2020.07.014.

He, Z., Weng, W., 2021. A risk assessment method for multi-hazard coupling disasters. Risk Anal. 41 (8), 1362–1375. https://doi.org/10.1111/risa.13628.

Howes, M., Dodson, J., Tomerini, D., 2013. Planning for Resilience in a Changing Climate: Integrating Spatial Analysis and On-Line Pollution Inventories to Manage Chemical Releases during Floods. Planning for Resilient Cities and Regions. AESOP & ACSP.

Huang, K., Chen, G., Yang, Y., Chen, P., 2020. An innovative quantitative analysis methodology for Natech events triggered by earthquakes in chemical tank farms. Saf. Sci. 128, 104744. https://doi.org/10.1016/j.ssci.2020.104744.

Huggel, C., Kääb, A., Salzmann, N., 2004. GIS-based modeling of glacial hazards and their interactions using Landsat-TM and IKONOS imagery. Nor. Geogr. Tidsskr. 58 (2), 61–73. https://doi.org/10.1080/00291950410002296.

Kameshwar, S., Padgett, J.E., 2014. Multi-hazard risk assessment of highway bridges subjected to earthquake and hurricane hazards. Eng. Struct. 78, 154–166. https://doi.org/10.1016/j.engstruct.2014.05.016.

Kappes, M.S., Keiler, M., von Elverfeldt, K., Glade, T., 2012. Challenges of analyzing multi-hazard risk: a review. Nat. Hazards 64 (2), 1925–1958. https://doi.org/10.1007/s11069-012-0294-2.

Khakzad, N., Van Gelder, P., 2018. Vulnerability of industrial plants to flood-induced natechs: a Bayesian network approach. Reliab. Eng. Syst. Saf. 169, 403–411. https://doi.org/10.1016/j.ress.2017.09.016.

Khakzad, N., Khan, F., Amyotte, P., 2011. Safety analysis in process facilities: comparison of fault tree and Bayesian network approaches. Reliab. Eng. Syst. Saf. 96 (8), 925–932. https://doi.org/10.1016/j.ress.2011.03.012.

Khakzad, N., Khan, F., Amyotte, P., 2013. Domino effect analysis using Bayesian networks. Risk Anal. 33, 292–306. https://doi.org/10.1111/j.1539-6924.2012.01854.x.

Khakzad, N., Reniers, G., Abbassi, R., Khan, F., 2016. Vulnerability analysis of process plants subject to domino effects. Reliab. Eng. Syst. Saf. 154, 127–136. https://doi.org/10.1016/j.ress.2016.06.004.

Khakzad, N., Landucci, G., Reniers, G., 2017a. Application of graph theory to cost-effective fire protection of chemical plants during domino effects. Risk Anal. 37 (9), 1652–1667. https://doi.org/10.1111/risa.12712.

Khakzad, N., Landucci, G., Reniers, G., 2017b. Application of dynamic Bayesian network to performance assessment of fire protection systems during domino effects. Reliab. Eng. Syst. Saf. 167, 232–247. https://doi.org/10.1016/j.ress.2017.06.004.

Khan, F.I., Abbasi, S.A., 1997. TOPHAZOP: a knowledge-based software tool for conducting HAZOP in a rapid, efficient yet inexpensive manner. J. Loss Prev. Process. Ind. 10 (5–6), 333–343. https://doi.org/10.1016/S0950-4230(97)00023-5.

Khan, F.I., Abbasi, S.A., 1998a. Multivariate hazard identification and ranking system. Process Saf. Prog. 17 (3), 157–170. https://doi.org/10.1002/prs.680170303.

Khan, F.I., Abbasi, S.A., 1998b. DOMIFFECT (DOMIno eFFECT): user-friendly software for domino effect analysis. Environ. Model. Software 13, 163–177. https://doi.org/10.1016/S1364-8152(98)00018-8.

Khan, F.I., Abbasi, S.A., 1999. PROFAT: a user friendly system for probabilistic fault tree analysis. Process Saf. Prog. 18 (1), 42–49. https://doi.org/10.1002/prs.680180109.

Khan, F., Rathnayaka, S., Ahmed, S., 2015. Methods and models in process safety and risk management: past, present and future. Process Saf. Environ. Protect. 98, 116–147. https://doi.org/10.1016/j.psep.2015.07.005.

Kim, D., Volk, H., Girirajan, S., Pendergrass, S., Hall, M.A., et al., 2017. The joint effect of air pollution exposure and copy number variation on risk for autism. Autism Res. 10 (9), 1470–1480. https://doi.org/10.1002/aur.1799.

Krausmann, E., Baranzini, D., 2012. Natech risk reduction in the European Union. J. Risk Res. 15 (8), 1027–1047. https://doi.org/10.1080/13669877.2012.666761.

Krausmann, E., Cruz, A.M., 2013. Impact of the 11 March 2011, Great East Japan earthquake and tsunami on the chemical industry. Nat. Hazards 67 (2), 811–828. https://doi.org/10.1007/s11069-013-0607-0.

Krausmann, E., Cruz, A.M., Salzano, E., 2016. Natech Risk Assessment and Management: Reducing the Risk of Natural-Hazard Impact on Hazardous Installations. Elsevier, Amsterdam.

Landucci, G., Argenti, F., Spadoni, G., Cozzani, V., 2016. Domino effect frequency assessment: the role of safety barriers. J. Loss Prev. Process. Ind. 44, 706–717. https://doi.org/10.1016/j.jlp.2016.03.006.

Lee, K.H., Rosowsky, D.V., 2006. Fragility analysis of woodframe buildings considering combined snow and earthquake loading. Struct. Saf. 28 (3), 289–303. https://doi.org/10.1016/j.strusafe.2005.08.002.

Li, J., Reniers, G., Cozzani, V., Khan, F., 2017. A bibliometric analysis of peer-reviewed publications on domino effects in the process industry. J. Loss Prev. Process. Ind. 49, 103–110. https://doi.org/10.1016/j.jlp.2016.06.003.

Markowski, A.S., Kotynia, A., 2011. "Bow-tie" model in layer of protection analysis. Process Saf. Environ. Protect. 89 (4), 205–213. https://doi.org/10.1016/j.psep.2011.04.005.

Mesa-Gómez, A., Casal, J., Muñoz, F., 2020. Risk analysis in Natech events: state of the art. J. Loss Prev. Process. Ind. 64, 104071. https://doi.org/10.1016/j.jlp.2020.104071.

Mesa-Gómez, A., Casal, J., Sánchez-Silva, M., Muñoz, F., 2021. Advances and gaps in natech quantitative risk analysis. Processes 9 (1), 40. https://doi.org/10.3390/pr9010040.

Misuri, A., Cozzani, V., 2021. A paradigm shift in the assessment of Natech scenarios in chemical and process facilities. Process Saf. Environ. Protect. https://doi.org/10.1016/j.psep.2021.06.018.

Misuri, A., Antonioni, G., Cozzani, V., 2020. Quantitative risk assessment of domino effect in Natech scenarios triggered by lightning. J. Loss Prev. Process. Ind. 64, 104095. https://doi.org/10.1016/j.jlp.2020.104095.

Necci, A., Cozzani, V., Spadoni, G., Khan, F., 2015. Assessment of domino effect: state of the art and research Needs. Reliab. Eng. Syst. Saf. 143, 3–18. https://doi.org/10.1016/j.ress.2015.05.017.

Necci, A., Krausmann, E., Girgin, S., 2018. Emergency planning and response for Natech accidents. In: Towards an All-Hazard Approach to Emergency Preparedness and Response–Lessons Learnt from Non-nuclear Events. OECD NEA, Paris, pp. 61–68.

Ni, H., Chen, A., Chen, N., 2010. Some extensions on risk matrix approach. Saf. Sci. 48 (10), 1269–1278. https://doi.org/10.1016/j.ssci.2010.04.005.

Official Journal of the European Union (OJEU), 1982. Council Directive 82/501/EEC of 24 June 1982 on the Major-Accident Hazards of Certain Industrial Activities. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A31982L0501. (Accessed 3 February 1999). accessed.

Official Journal of the European Union (OJEU), 1996. Council Directive 96/82/EC of 9 December 1996 on the control of major-accident hazards involving dangerous substance. https://eur-lex.europa.eu/eli/dir/1996/82/oj/. (Accessed 13 August 2012). accessed.

Official Journal of the European Union (OJEU), 2012. Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances. https://eur-lex.europa.eu/eli/dir/2012/18/oj. (Accessed 23 July 2012). accessed.

Omidvar, B., Kivi, H.K., 2016. Multi-hazard failure probability analysis of gas pipelines for earthquake shaking, ground failure and fire following earthquake. Nat. Hazards 82 (1), 703–720. https://doi.org/10.1007/s11069-016-2214-3.

Papadakis, G., Amendola, A., 1997. Guidance on the Preparation of a Safety Report to Meet the Requirements of Council Directive 96/82/EC (Seveso II). Joint Research Centre, European Commission.

Qian, F., Chen, L., Li, J., Ding, C., Chen, X., Wang, J., 2019. Direct prediction of the toxic gas diffusion rule in a real environment based on LSTM. Int. J. Environ. Res. Publ. Health 16 (12), 2133. https://doi.org/10.3390/ijerph16122133.

Qin, R., Zhu, J., Khakzad, N., 2020. Multi-hazard failure assessment of atmospheric storage tanks during hurricanes. J. Loss Prev. Process. Ind. 68, 104325. https://doi.org/10.1016/j.jlp.2020.104325.

Rad, A., Abdolhamidzadeh, B., Abbasi, T., Rashtchian, D., 2014. Freedom II: an improved methodology to assess domino effect frequency using simulation techniques. Process Saf. Environ. Protect. 92, 714–722. https://doi.org/10.1016/j.psep.2013.12.002.

Remo, J.W., Pinter, N., 2012. Hazus-MH earthquake modeling in the central USA. Nat. Hazards 63 (2), 1055–1081. https://doi.org/10.1007/s11069-012-0206-5.

Reniers, G., 2010. An external domino effects investment approach to improve cross-plant safety within chemical clusters. J. Hazard Mater. 177 (1–3), 167–174. https://doi.org/10.1016/j.jhazmat.2009.12.013.

Reniers, G., Cozzani, V., 2013. Domino Effects in the Process Industries: Modelling, Prevention and Managing. Elsevier, Amsterdam.

Reniers, G., Dullaert, W., Karel, S., 2009. Domino effects within a chemical cluster: a game-theoretical modeling approach by using Nash-equilibrium. J. Hazard Mater. 167, 289–293. https://doi.org/10.1016/j.jhazmat.2008.12.113.

Reniers, G., Cuypers, S., Pavlova, Y., 2012. A game-theory based multi-plant collaboration model (MCM) for cross-plant prevention in a chemical cluster. J. Hazard Mater. 209, 164–176. https://doi.org/10.1016/j.jhazmat.2012.01.004.

Ricci, F., Moreno, V.C., Cozzani, V., 2021. A comprehensive analysis of the occurrence of Natech events in the process industry. Process Saf. Environ. Protect. 147, 703–713. https://doi.org/10.1016/j.psep.2020.12.031.

Rossa, C.G., Fernandes, P.M., 2018. An empirical model for the effect of wind on fire spread rate. Fire 1 (2), 31. https://doi.org/10.3390/fire1020031.

Salzano, E., Basco, A., Busini, V., Cozzani, V., Marzo, E., Rota, R., Spadoni, G., 2013. Public awareness promoting new or emerging risks: industrial accidents triggered by natural hazards (NaTech). J. Risk Res. 16 (3–4), 469–485. https://doi.org/10.1080/13669877.2012.729529.

Society of Fire Protection Engineers (SFPE), 2016. SFPE Handbook of Fire Protection Engineering, fifth ed. Springer, New York.

Showalter, P.S., Myers, M.F., 1994. Natural disasters in the United States as Release agents of oil, chemicals, or radiological materials between 1980–1989: analysis and recommendations. Risk Anal. 14 (2), 169–182. https://doi.org/10.1111/j.1539-6924.1994.tb00042.x.

Soto, D., Renard, F., 2015. New prospects for the spatialisation of technological risks by combining hazard and the vulnerability of assets. Nat. Hazards 79 (3), 1531–1548. https://doi.org/10.1007/s11069-015-1912-6.

Steinberg, L.J., Sengul, H., Cruz, A.M., 2008. Natech risk and management: an assessment of the state of the art. Nat. Hazards 46 (2), 143–152. https://doi.org/10.1007/s11069-007-9205-3.

Stelzenmüller, V., Coll, M., Mazaris, A.D., Giakoumi, S., Katsanevakis, S., et al., 2018. A risk-based approach to cumulative effect assessments for marine management. Sci. Total Environ. 612, 1132–1140. https://doi.org/10.1016/j.scitotenv.2017.08.289.

Stelzenmüller, V., Coll, M., Cormier, R., Mazaris, A.D., Pascual, M., et al., 2020. Operationalizing risk-based cumulative effect assessments in the marine environment. Sci. Total Environ. 724, 138118. https://doi.org/10.1016/j.scitotenv.2020.138118.

Sun, B., Guo, K., 2013. LNG accident dynamic simulation: application for hazardous consequence reduction. J. Loss Prev. Process. Ind. 26 (6), 1246–1256. https://doi.org/10.1016/j.jlp.2013.06.005.

Sun, D., Jiang, J., Zhang, M., Wang, Z., 2015. Influence of the source size on domino effect risk caused by fragments. J. Loss Prev. Process. Ind. 35, 211–223. https://doi.org/10.1016/j.jlp.2015.05.005.

Sun, D., Jiang, J., Zhang, M., Wang, Z., Zhang, Y., Cai, L., 2016. Investigation of multiple domino scenarios caused by fragments. J. Loss Prev. Process. Ind. 40, 591–602. https://doi.org/10.1016/j.jlp.2016.01.023.

Swuste, P., van Nunen, K., Reniers, G., Khakzad, N., 2019. Domino effects in chemical factories and clusters: an historical perspective and discussion. Process Saf. Environ. Protect. 124, 18–30. https://doi.org/10.1016/j.psep.2019.01.015.

Tarvainen, T., Jarva, J., Greiving, S., 2006. Spatial pattern of hazards and hazard interactions in Europe. Geol. Surv. Finland Spec. Paper. 42, 83–91.

Netherlands Organisation for Applied Scientific Research (TNO), 1992. Methods for the Determination of Possible Damage to People and Objects Resulting from Releases of Hazardous Materials. Green Book). Committee for the Prevention of Disasters, The Hague.

Netherlands Organisation for Applied Scientific Research (TNO), 1997. Methods for Determining and Processing Probabilities (Red Book). Committee for the Prevention of Disasters, The Hague.

Netherlands Organisation for Applied Scientific Research (TNO), 1999. Guidelines for Quantitative Risk Assessment (Purple Book). Committee for the Prevention of Disasters, The Hague.

Netherlands Organisation for Applied Scientific Research (TNO), 2005. Methods for the Calculation of Physical Effects: Due to Releases of Hazardous Materials (Liquids and Gases) (Yellow Book). Committee for the Prevention of Disasters, The Hague.

United Nations Office for Disaster Risk Reduction (UNDRR), 2005. Hyogo Framework for Action 2005–2015: Building the Resilience of Nations and Communities to Disasters. https://www.unisdr.org/2005/wcdr/intergover/official-doc/L-docs/Hyogo-framework-for-action-english.pdf. (Accessed 22 January 2005). accessed.

United Nations Office for Disaster Risk Reduction (UNDRR), 2015a. Sendai Framework for Disaster Risk Reduction 2015–2030. https://www.preventionweb.net/files/resolutions/N1516716.pdf. (Accessed 3 June 2015). accessed.

United Nations Office for Disaster Risk Reduction (UNDRR), 2015b. Proposed Updated Terminology on Disaster Risk Reduction: A Technical Review. https://www.unisdr.org/files/45462_backgoundpaperonterminologyaugust20.pdf. (Accessed 20 August 2015). accessed.

United Nations, 1992. Agenda 21. https://sustainabledevelopment.un.org/outcomedocuments/agenda21. (Accessed 4 September 2002). accessed.

United Nations, 2017. Toward a Global Pact for the Environment white paper. https://globalpactenvironment.org/uploads/White-paper-Global-pact-for-the-environment.pdf. (Accessed 10 May 2018). accessed.

Valsamos, G., Larcher, M., Casadei, F., 2021. Beirut explosion 2020: a case study for a large-scale urban blast simulation. Saf. Sci. 137, 105190. https://doi.org/10.1016/j.ssci.2021.105190.

Wang, H.X., 2016. Non-linear Measurement and its Applications in Finance. Economy & management publishing house, Beijing.

Wang, J., He, Z., Weng, W., 2020. A review of the research into the relations between hazards in multi-hazard risk analysis. Nat. Hazards 104 (3), 2003–2026. https://doi.org/10.1007/s11069-020-04259-3.

Węgrzyński, W., Lipecki, T., 2018. Wind and fire coupled modelling—Part I: literature review. Fire Technol. 54 (5), 1405–1442. https://doi.org/10.1007/s10694-018-0748-5.

Wu, J., Yang, H., Cheng, Y., Nishi, T., Cheng, T.C.E., 2020. An N-Enterprise investment game under risk of domino accidents in a chemical cluster: nash and pareto equilibria. Comput. Chem. Eng. 134, 106705. https://doi.org/10.1016/j.compchemeng.2019.106705.

Zeng, T., Chen, G., Reniers, G., Yang, Y., 2021. Methodology for quantitative risk analysis of domino effects triggered by flood. Process Saf. Environ. Protect. 147, 866–877. https://doi.org/10.1016/j.psep.2020.12.042.

Zhang, X.M., Chen, C., 2013. Mechanism analysis and risk assessment of escalation scenario in chemical industry zones. Process Saf. Environ. Protect. 91 (1–2), 79–85. https://doi.org/10.1016/j.psep.2012.02.003.

Zhang, J., Glezakou, V.A., 2021. Global optimization of chemical cluster structures: methods, applications, and challenges. Int. J. Quant. Chem. 121, e26553 https://doi.org/10.1002/qua.26553.

Zhang, L., Reniers, G., Chen, B., Qiu, X., 2018. Integrating the API SRA methodology and game theory for improving chemical plant protection. J. Loss Prev. Process. Ind. 51, 8–16. https://doi.org/10.1016/j.jlp.2017.11.002.

Zhou, J., Reniers, G., 2017. Analysis of emergency response actions for preventing fire-induced domino effects based on an approach of reversed fuzzy Petri-net. J. Loss Prev. Process. Ind. 47, 169–173. https://doi.org/10.1016/j.jlp.2017.03.011.

Zhou, J., Reniers, G., 2018a. Petri-net based evaluation of emergency response actions for preventing domino effects triggered by fire. J. Loss Prev. Process. Ind. 51, 94–101. https://doi.org/10.1016/j.jlp.2017.12.001.

Zhou, J., Reniers, G., 2018b. A matrix-based modelling for fire induced domino effects. Process Saf. Environ. Protect. 116, 347–353. https://doi.org/10.1016/j.psep.2018.02.014.

Zuccaro, G., Cacace, F., Spence, R.J.S., Baxter, P.J., 2008. Impact of explosive eruption scenarios at Vesuvius. J. Volcanol. Geoth. Res. 178 (3), 416–453. https://doi.org/10.1016/j.jvolgeores.2008.01.005.