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Resilience assessment of chemical industrial areas during Natech-related cascading multi-hazards

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ABSTRACT

In chemical industrial areas, technological accidents triggered by natural events (Natech events) may escalate. Complex cascading multi-hazard scenarios with high uncertainties may be caused. Resilience is an essential property of a system to withstand and recover from disruptive events. The present study focuses on the change of the resilience level due to (possible) interactions between cascading hazards, chemical installations and safety barriers during the dynamic evolution of fire escalations triggered by a natural hazard (certain cascading multi-hazard scenarios). A quantitative resilience assessment method is developed to this end. The state transition of a system facing accidents in the context of resilience is explored. Moreover, the uncertainties accompanying an accident evolution are quantified using a Dynamic Bayesian Network, allowing a detailed analysis of the system performance in different time steps. System resilience is measured as a time-dependent function with respect to the change of system performance. The applicability of the proposed methodology is demonstrated by a case study, and the effects of different configurations of safety barriers on improving resilience are discussed. The results are valuable to support disaster prevention within chemical industrial areas.

1. Introduction

With the development of the process industry, many chemical industrial areas have emerged around the world. Except for the positive effects on countries' economies, the clustering of hazardous materials and processes increases the possibility of a single mishap propagating to nearby units (so-called domino effects), posing important threats to industry and society (Chen et al., 2020a, b, 2021a; Heikkila et al., 2010; Reniers et al., 2014). In addition to conventional causes (process malfunctioning or human error), the potential for natural events to trigger fires, explosions or releases of chemical substances should not be ignored. Those technological effects triggered by natural events, so-called Natech accidents, have been emphasized in the safety domain (Camila et al., 2019; Krausmann et al., 2016; Nascimento and Alencar, 2016; Steinberg et al., 2008). Previous studies of accident statistics (Cozzani et al., 2010; Girgin and Krausmann, 2016; Kumasaki et al., 2017; Ricci et al., 2021) showed that the consequences of Natech accidents usually are more severe than conventional accidents. Moreover, natural events can cause multiple failures in a very short time and may damage or destroy safety barriers and lifeline systems, leading to complex accident scenarios and to possible rapid propagation of the initial technological undesired events. In particular, multiple disaster factors involved in the evolution of accidents, may lead to non-linear interactions between successive hazardous events. The phenomenon which can be called 'Natech-related multi-hazard cascading effect', should not be neglected due to its potential catastrophic consequences. For instance, on August 17, 1999, a disaster, the Kocaeli earthquake, had an impact on the industrial areas of Turkey, causing massive fires in the TUPRAS Izmit refinery through domino effects (Girgin, 2011). On March 11, 2011, the Great East Japan earthquake and tsunami triggered major fires and explosions in Sendai and Chiba, destroying more than 20 tanks and causing huge releases of hazardous materials (Krausmann and Cruz, 2013). There are many complex interactions between hazards, installations, and safety barriers in Natech-related multi-hazard cascading scenarios. Those interactions may further evolve with time and space, therefore developing an effective disaster mitigation and prevention

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strategy is a complex and comprehensive task.

The term “resilience” has been widely employed in many domains, such as engineering, ecology, economics, etc., representing the ability of a system to resist disturbances and the ability to bounce back to normal operations (Kinzig et al., 2006; Maler, 2008; Perrings, 2006). In the engineering domain, the resilience of infrastructure systems (e.g., transportation, power grid, water supply, etc.) has mainly been paid attention to (Baroud et al., 2015; Henry and Ramirez-Marquez, 2012; Kong and Simonovic, 2018; Kong et al., 2019, 2021; Zhang et al., 2018a, b). The impact of multiple disruptive events at once, and the interdependence among infrastructure systems and cascading failures are also considered in certain resilience studies (Kong and Simonovic, 2018). Moreover, Kong et al. (2019) pointed out that the effects of several hazards at once on infrastructure system resilience are more complicated than simply the sum of the single hazards. Recently, the resilience concept has been introduced into the field of process safety (Cincotta et al., 2019; Dinh et al., 2012; Jain et al., 2018; Zinetullina et al., 2021), providing a new insight into the strategy of disaster mitigation and prevention. A resilient system could adjust prior or following the disturbances to withstand and recover quickly in case of disruptive events. Several scholars defined different resilience concepts according to the characteristics of the system of interest and developed qualitative or quantitative methods to evaluate system resilience (Cincotta et al., 2019; Henry and Ramirez-Marquez, 2012; Kammouh et al., 2020). The results of resilience assessment are helpful to guide targeted prevention, preparedness, response and recovery activities in an investigated area. Nevertheless, due to the presence of uncertainties as a result of the impact of cascading hazards, evaluating the system resilience of a chemical industrial area in the case of multi-hazard cascading scenarios, still is a challenge.

Cascading events need to be understood not only regarding the primary effects, but also in the broader context of damage effects. In the field of process safety, the research on the uncertainty of domino effects is in a relative mature phase. Many methods such as graph theory (Chen et al., 2018, 2019; Khakzad et al., 2017b), Monte Carlo simulation (Abdolhamidzadeh et al., 2010; Chen et al., 2021b; Huang et al., 2021; Lisi et al., 2015), Bayesian Network (BN) (Khakzad et al., 2013, 2014; Naderpour and Khakzad, 2018), Dynamic Bayesian Network (DBN) (Khakzad, 2015, 2018; Khakzad et al., 2017a), Petri-net (Kamil et al., 2019; Zhou and Reniers, 2018b, 2021), fire synergistic effect model (FSEM) (Ding et al., 2019, 2020), matrix-based model (Zhou and Reniers, 2018a, 2020) have been developed for the evolution modeling of domino effects and probability estimation of accident escalation. Besides, “Natech events” as an emerging concept has been paid more attention to over the past decades (Camila et al., 2019; Nascimento and Alencar, 2016; Young et al., 2004). Previous studies have made contributions to the vulnerability assessment of process units to natural hazards (Campedel et al., 2008; Kameshwar and Padgett, 2018; Khakzad and Van Gelder, 2017, 2018; Landucci et al., 2012; Lanzano et al., 2013; Qin et al., 2020; Salzano et al., 2003; Yang et al., 2020). The potential collapse or structural damage of installations or equipment due to natural events can be evaluated from the perspective of probability. In recent years, uncertainties related to the escalation during Natech events have been discussed. Some scholars (Huang et al., 2020; Misuri et al., 2020a; Yang et al., 2018) argued that the probabilities and consequences of domino chains triggered by natural events increase rapidly due to higher probabilities of simultaneous primary events and faster evolution of accidents, leading to more complex accident scenarios.

In order to prevent or mitigate possible technological accidents, the physical and non-physical measures that serve safety functions are adopted in the process industry, which usually are called ‘safety barriers’ in the technical literature (Khakzad, 2018; Khakzad et al., 2017a; Landucci et al., 2015). In the view of resilience engineering, safety barriers can effectively recognize and absorb the disturbances and disruptions to a system, preventing accident propagation and reducing potential losses. Moreover, if the safety barriers impede accident evolution successfully, a process system is able to return to the normal state early. Therefore, the performance of safety barriers and their associated uncertainties is important for resilience assessment. Some related research has been carried out. Landucci et al. (2015) quantitatively evaluated the prevention performance of different types of safety barriers for fire-related domino effects and then revised the probit models for the calculation of escalation probability. Misuri et al. (2020b) quantitatively assessed the performance degradation of safety barriers in the case of natural events (floods and earthquakes). Next, Misuri et al. (2021) estimated the frequency of secondary domino scenarios during Natech events by incorporating their previous research about safety barriers (Misuri et al., 2020b). Cincotta et al. (2019) highlighted that timely firefighting could increase the resilience of chemical plants with respect to fire-related domino scenarios and proposed a resilience metric to investigate the best firefighting strategy. However, on the one hand, unlike the conventional domino effects, the safety barriers may fail due to natural events, introducing more uncertainties to resilience assessment. On the other hand, evaluating the system resilience during cascading events is hard due to the complex interactions of hazards, chemical installations, and safety barriers.

The present study aims to develop a quantitative resilience assessment approach for chemical industrial areas considering complex interactions of successive disruptive events, chemical installations, and safety barriers in Natech-related cascading multi-hazard scenarios. The approach can be applied to fire domino effects triggered by any kind of natural event. The uncertainties related to accident evolution and performance degradation of safety barriers are quantified using DBN. Moreover, a time-dependent function of system performance is defined, which depicts the temporal changes of possible economic loss for the overall system. The system resilience is evaluated using the classic model of time-series performance change, allowing a detailed dynamic analysis of the system resilience to Natech-related cascading multi-hazard scenarios. The application and significance of the developed approach are illustrated by a case study. The effects of different configurations of safety barriers on enhancing system resilience can be compared, allowing a proactive development and adoption of safety measures before accidents actually take place, which is meaningful to reduce the impacts of a natural event on chemical industrial areas.

This paper is organized as follows. Section 2 defines Natech-related cascading multi-hazards in chemical industrial areas and introduces the probability model for accidental escalation. System resilience in Natech-related cascading multi-hazard scenarios and corresponding performance state transition is discussed in Section 3. Next, the general methodology for assessing the resilience of chemical industrial areas is developed in Section 4. A case study is provided in Section 5 and the conclusions drawn from this study are presented in Section 6.

2. Natech-related cascading multi-hazards in chemical industrial areas

2.1. Characteristic of Natech-related cascading multi-hazard

The concept of ‘multi-hazard’ was emphasized in some official documents, like UN ‘Agenda 21’ (UNCED, 1992) and the UN Hyogo Framework for Action 2005–2015 (UNISDR, 2005). However, the early ‘multi-hazard’ concept is focused on the interrelationships between multiple natural hazards (Tilloy et al., 2019). With the deepening of research, all possible hazards (natural hazards and man-made hazards) are incorporated into the multi-hazard framework. Cascading disasters are of particular interest in the studies of multi-hazards since successive disruptive events with a triggering relationship may lead to more severe consequences than the sum of single-hazard effects. Many terms are used to describe the triggering relationship within different types of hazards, like disaster chains (a natural hazard triggers one or more other natural hazards), Natech events (a natural event triggers a technological disaster), domino effects (a primary industrial accident triggers a secondary (and perhaps higher-order) industrial accident), or Natech domino effects (domino effects triggered by natural events). Natech domino effects as a complex case that may occur in chemical industrial areas, involving cross-category hazards, accident chains and concurrent technological hazards, deserve more attention.

For cascading disasters, Alexander (2018) summarized three main elements, namely 'cause', 'effect', and 'escalation point', and proposed a preliminary magnitude scale. Considering the characteristics and possible evolution of Natech domino effects, the magnitude scale for the Natech-related cascading multi-hazard events is further discussed, as shown in Table 1.

Table 1 also provides a detailed hierarchical framework for accident dynamic analysis. Specifically, Magnitude 0 represents the initiation condition of Natech-related cascading multi-hazards; Magnitude 1 leads to possible loss of containment (LOC) scenarios; Magnitude 2 and 3 show the possible primary scenarios after LOC events; and Magnitude 4 and 5 describe the accident propagation triggered by primary scenarios. Compared to explosion-related domino effects, fire-related domino effects are more time-dependent, since a fire usually lasts for a longer period of time and generates escalation vectors during the escalation process. Therefore, we focus in this paper on fire-related domino effects triggered by natural events (a typical type of Natech-related cascading multi-hazard) and aim to develop a resilience assessment methodology for chemical industrial areas considering certain scenarios.

2.2. Relationships between hazards, installations and safety barriers

In order to prevent and mitigate possible domino effects in the process industry, some scholars identified three categories of safety barriers by adopting the classification of protection layers, including: i) active barriers; ii) passive barriers; and iii) procedural barriers (Khakzad et al., 2017b; Landucci et al., 2015; Misuri et al., 2020b, 2021). Although inherently safer design as a safety layer has an important effect on the reduction of domino effects (e.g., due to adopting a safety distance or by using safety inventories), it is not deemed a safety barrier in actual accident propagation since its application is limited to the early design stage (Khakzad et al., 2017a). In this paper, we addressed only active and passive barriers, excluding procedural barriers. This is due to the high complexity and uncertainties related to procedural and emergency measures, requiring a performance assessment approach considering human factors being out of the scope of the present study.

According to the location of hazard source (inside or outside of the chemical industrial area), associating disturbances on the area can be divided into external disturbance (e.g., disturbance due to natural hazards) and internal disturbance (e.g., disturbance due to domino effects). In Natech-related cascading multi-hazard scenarios, external and internal disturbances are generated successively and act on the chemical industrial area, damaging chemical units and possibly resulting in subsequent accidents. Clearly enough, the impact of hazard disturbances is negative to system safety. Safety barriers are employed to protect chemical units by preventing or mitigating the influence of internal disturbances, which can be seen as positive actions on system safety. However, safety barriers also may be damaged due to domino effects, for instance, the performance degradation of a fireproofing layer in severe fire conditions. Moreover, several recent studies pointed out that natural hazards may deplete the availability of safety barriers, and even render safety barriers inoperable (Krausmann et al., 2016; Misuri et al., 2020b, 2021). Damaged safety barriers cannot provide effective protection for chemical units, resulting in a negative effect on system safety. Those mutually exclusive effects lead to complex relationships between hazards, installations, and safety barriers, as shown in Fig. 1.

Table 1
The magnitude scale for Natech-related cascading multi-hazards. (Developed from Alexander (2018)).

Magnitude	Description	Example (a flood as the initiating cause)
0	A simple relationship between natural event and its physical effect, without significant damage to chemical units.	A flood impacts a chemical industrial area, but no unit has been damaged.
1	A short cascade between natural event, primary physical effect and secondary damage effect, without primary event for domino propagation.	A flood impacts a chemical industrial area, one or more units have been damaged due to flood impacts, but don't lead to fire or explosion.
2	Significant cascading chain between natural event and primary accident, without accident escalation.	A flood impacts a chemical industrial area, one damaged unit is firing or exploded, but the escalation vector is not sufficient to trigger secondary accidents.
3	Significant cascading chains between natural event and more than one primary accidents, without accident escalation.	A flood impacts a chemical industrial area, leading to multi-source primary accident scenarios, while no secondary accident occurs.
4	Significant cascading chains between natural event and primary accident(s), the following accident propagation pattern is a straight-cascading-chain.	A flood impacts a chemical industrial area, leading to primary accident scenario(s). Then, the primary scenario(s) trigger one secondary scenario, the secondary scenario triggers a tertiary scenario, and propagates in this way.
5	Significant cascading chains between natural event and primary accident(s), result in the complex multi-level propagation through synergistic effects and parallel effects.	A flood impacts a chemical industrial area, leading to primary accident scenario(s). The primary scenario(s) trigger several secondary scenarios, then triggering several tertiary scenarios, and so on.

2.3. Escalation probability assessment

For the estimation of the escalation probability in Natech-related cascading multi-hazard scenarios, it is essential to calculate the probability of LOCs of chemical units due to a disruptive natural event. To this end, vulnerability assessment is developed to yield a conservative estimation of chemical unit failure probability by vulnerability models or specific vulnerability curves (Campedel et al., 2008; Huang et al., 2020; Kameshwar and Padgett, 2018; Khakzad and Van Gelder, 2017, 2018; Landucci et al., 2012; Lanzano et al., 2013; Necci et al., 2016; Qin et al., 2020; Salzano et al., 2003; Yang et al., 2020; Zeng et al., 2021).

LOC events may lead to primary fires if hazardous materials are ignited. A probit model can be used to calculate the escalation probability of fire-related domino effects (P_e), as follows (Landucci et al., 2015):

$$\begin{cases} P_e = \dfrac{1}{\sqrt{2\pi}} \displaystyle\int_{-\infty}^{Y-5} \exp\left(-u^2/2\right) \mathrm{d}u \\ Y = 9.261 - 1.85 \ln(ttf) \end{cases} \tag{1}$$

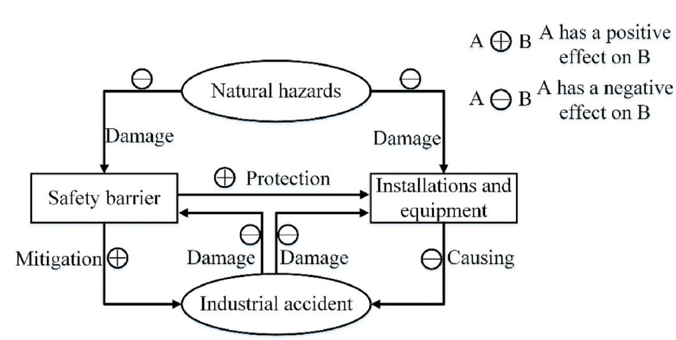


Fig. 1. The systemic relationships between hazards, installations and safety barriers.

where Y is the probit value.

Considering the effects of safety barriers, Landucci et al. (2015) have developed the estimation equations of the time to failure (*ttf*) of target units (as shown in Table 2). The *ttf* value calculated by the equations in Table 2 is a theoretical estimation, and a more precise assessment of *ttf* could improve the credibility of the escalation model.

$$\begin{cases} PFD = 1 + (\phi - 1) \times (1 - PFD_0); \eta = \eta_0(\text{activebarrier}) \\ \eta = \eta_0(1 - \phi)(\text{passivebarrier}) \end{cases} \quad (2)$$

where *PFD* is the probability of failure on demand, representing the unavailability of safety barrier; Φ is the performance modification factor for a safety barrier facing a natural event; η is the effectiveness of a safety barrier; PFD_0 and η_0 are the baseline unavailability and effectiveness values, respectively, i.e., performance values of a safety barrier in the absence of any natural event. Examples of available safety barriers and reference values of performance parameters are reported in Table 3.

3. System resilience in Natech-related cascading multi-hazard scenario

3.1. Performance state transition in the context of resilience

For a process system consisting of process units and surrounding safety barriers, its resilience exhibits different performance levels. As shown in Fig. 2, three states are divided to describe the performance state transition for a resilient process system, including steady state, transition state and accident state.

The system originally dwells on a steady state with high performance before the disturbance impacts it. The system would subsequently enter the transition state, whereafter some resilience characteristics are put into action for resisting the damage of disruptive events. In this stage, the system could bounce back to the steady state if the resilient features effectively stop the disturbances, otherwise the system state would transfer to the accident state. In particular, the transition state may be skipped quickly if the system cannot resist the disruptive event. In the accident state, system performance would be degraded until reaching a minimum value, while system resilience delays the rate of performance degradation. Finally, some strong interventions need to be carried out to save the system and restore its performance to a steady state. It is noted that the stable system after the accident state could have the same, similar or different performance as the original system.

In Natech-related cascading multi-hazard scenarios, multiple hazards occur successively in a relative short time (maybe a few hours or minutes), there is not enough time for effective recovery during the process of accident evolution. Besides, the disturbances and system behaviors may change over time. Regarding the cascading scenarios as a single disruptive event is oversimplified. To analyze the state of the chemical industrial area in detail, the cascading multi-hazard scenarios can be divided into several accident stages (e.g., Natech stage, first-level domino effect, second-level domino effect, etc.) according to the dominant hazard source, and performance state transition in different accident stage are further discussed in Section 3.2.

Table 2
Quantitative assessment model for *ttf* considering the role of safety barriers. (*V*: the volume of target unit, m^3; *Q*: heat radiation received by target unit, kW/m^2; α: intensity reduction factor of water deluge system; Q_0: original heat radiation received by target unit, kW/m^2; ttf_p: the time to failure of target unit in presence of fire protection; $\triangle t$: the further time to the time to failure provided by fireproof layer) (Landucci et al., 2015).

Primary accident	Threshold	Estimation of *ttf*
Pool fire or jet fire	For atmospheric unit 15 kW/m^2 For pressurized unit 45 kW/m^2	For atmospheric unit $ttf = 0.0167 \times \exp(-2.667 \times 10^{-5}V\text{-}1.13\ln Q\text{+}9.877)$ For pressurized unit $ttf = 0.0167 \times \exp(8.845 \times V^{0.032}\text{-}0.95\ln Q)$ In case of available water deluge system $Q=(1\text{-}\alpha) \times Q_0$ In case of available fireproof layer $ttf_p = ttf + \triangle t$

Indeed, safety barriers may be damaged by natural events, which is a fact that should also be considered in the estimation of escalation probabilities. When a safety barrier is exposed to a natural event, the performance parameters can be modified as follows (Misuri et al., 2020b, 2021).

Table 3
Examples of available fire protection safety barriers and performance parameters (Retrieved from literature (Khakzad et al., 2017a; McNay et al., 2019; Misuri et al., 2020a; b, 2021)).

Safety barrier	PFD_0 (Reference value)	η_0 (Reference value)	Φ_e	Φ_f
Inert-gas blanketing system	5.0×10^{-3}	1	0.625	0.5
Automatic rim-seal fire extinguishers	8.1×10^{-3}	1	0.5	0.15
Fixed/Semi-fixed foam system	5.32×10^{-3}	0.954	0.5	0.375
WDS/Water curtains/ Sprinklers	4.33×10^{-2}	1	0.75	0.375
Shut down values	3.72×10^{-4}	1	0.5	0.25
Fire wall	/	1	0.5	0.2
Fireproofing	/	0.999	0.25	0.15

Φ_e and Φ_f are the performance modification factor for a safety barrier in case of earthquake and flood, respectively.

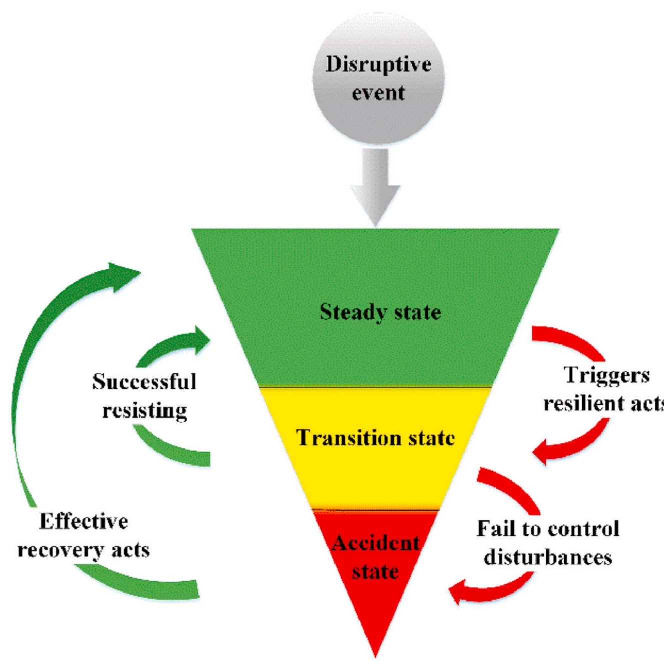


Fig. 2. Performance state transition in the context of resilience (modified after Dinh et al. (2012)).

3.2. Resilience function

By identifying the figure-of-merit of system over time, Henry and Ramirez-Marquez (2012) developed a general equation to calculate the value of resilience $R(t|e_j)$ in a certain time t after a disruptive event e_j:

$$R(t|e_j) = \frac{\varphi(t|e_j) - \varphi(t_d|e_j)}{\varphi(t_0) - \varphi(t_d|e_j)} \quad (3)$$

where $\varphi(\cdot)$ is a time-dependent delivery function to measure system performance; $\varphi(t_0)$ is the original system performance before e_j occurs; and $\varphi(t_d|e_j)$ is the system's lowest performance related to e_j.

Fig. 3 illustrates the performance change of a system facing Natech-related cascading multi-hazard scenarios. A complete process of performance state transition from the old steady state to a new steady state is shown. To discuss the performance change of the system in detail, three main phases are further elaborated: (i) the Natech phase, (ii) the escalation phase, and (iii) the recovery phase.

Before the occurrence of a disruptive event, the chemical industrial area (which is 'the system') is safe with full performance (φ_0). When the natural event hits the system (t_n), the performance may drop immediately due to the damage of one or several chemical units. Meanwhile, the system enters the accident state, the system performance is further reduced until the primary fires occur at t_p (the lowest system performance in the Natech phase). The primary accidents may escalate to the nearby chemical units, resulting in fire propagation. However, multi-level fire propagation would generate time-variant internal disturbances to the system. To discuss the performance change in the escalation phase, the cascading fires can be discretized according to the domino level. For example, in the first level of domino effects (t_p - t_s), the disruptive primary fires generate disturbances to the rest of the system (denotes rest-system). It is assumed that the rest-system is in the steady state with its peak performance. Then, the rest-system enters the transition state and the loss of system performance could be limited in the primary accidents if the intervention of safety barriers could impede the fire propagation. Otherwise, secondary accidents occur (t_s), denoting the rest-system enters the accident state. For the whole system, the performance further drops due to secondary fires. Similarly, the performance state transition for a new rest-system would be repeated in the second level of domino effects, the third level of domino effects, and so on, until no further possible escalation occurs (t_d). At that time, the system performance reaches the minimum value. The lowest performance level may last for a certain period until the recovery actions start (t_d'). Through a series of recovery actions, like site cleanup, equipment repair or replacement, functional tests, etc., the system returns to a new steady state (t_r) that may be different from the original state. However, in real cases, the recovery phase is a long-term and complex process, needing a detailed plan for multi-task completion. In the present study, we focus on the resilience of a process system during Natech-related cascading multi-hazard events, i.e., the system resilience in the Natech phase and the escalation phase.

For a process system consisting of n units in a Natech-related cascading multi-hazard scenario, let us assume that m units may be damaged at time t, the value of the i-th unit and its inventory are v_i and u_i, respectively, and the system performance at time t is defined as:

$$\varphi\left(t\middle|e_k\right)=\frac{v_{re}}{v_{total}}=\frac{\sum_{i=1}^{n}(v_i+u_i)-\sum_{i=1}^{n}[(v_i+u_i)\times P(i|e_k,t)]}{\sum_{i=1}^{n}(v_i+u_i)} \tag{4}$$

where v_{total} is the total value of all units and all inventories in the process system before the occurrence of the accident; v_{re} is the residual value of the process system at time t; and $P(i|e_k,t)$ is the damage probability of the i-th unit under the impact of event e_k at time t. The difference of unit properties (e.g., filling degree, the inventory in unit) can be reflected via the difference of the value of chemical unit and its inventory. The system performance metric is time-dependent since more units may get involved in the Natech-related cascading multi-hazard scenarios with time.

4. General methodology for assessing the resilience

4.1. Basic procedure

To explore the resisting ability of a process system to the cascading natural-technological accidents, a quantitative resilience assessment procedure is developed. The developed methodology provides a temporal view for system resilience with the accident evolution, considering the vulnerability of chemical units and the performance of safety barriers. The procedure of the methodology is outlined in Fig. 4, which is comprised of six steps.

The six steps are explained hereafter.

Step 1. All relevant data for resilience assessment is collected to perform the characterization of the natural event and the main features of the concerned industrial area. The preliminary information to be collected includes:

i) characteristics of natural events. The intensity of the natural event is a key parameter to characterize its impact, which could be used as the input of the vulnerability model, like the height and velocity of a flood, or the peak ground acceleration (PGA) of an earthquake;
ii) feature parameters of chemical units, illustrating their position in the investigated area and characteristics of each unit. The position of chemical units can be derived from the layout of the concerned area. The characteristics of each unit include the unit type, dimension parameters, the inventory and filling degree, the value of chemical unit and its inventory, etc.;
iii) characteristics of safety barriers, like the type of safety barriers (active or passive), the PFD_0 and η_0 value of each safety barrier, etc.;

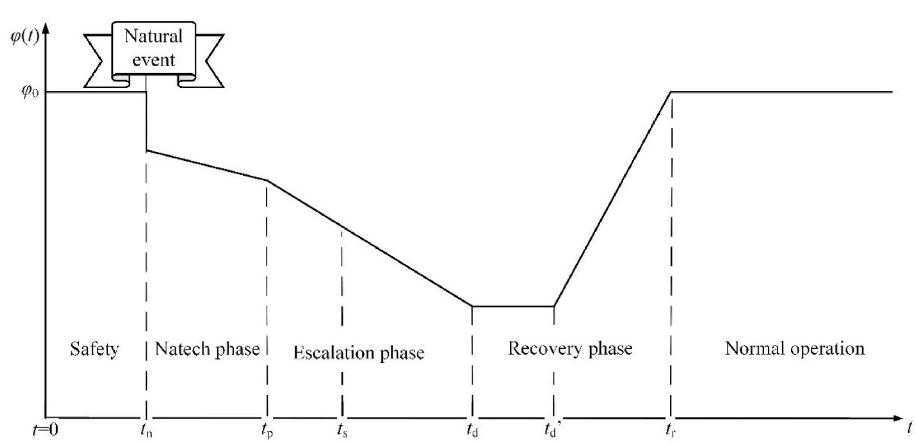


Fig. 3. An illustrative curve of system performance over time (modified after Cincotta et al., 2019).

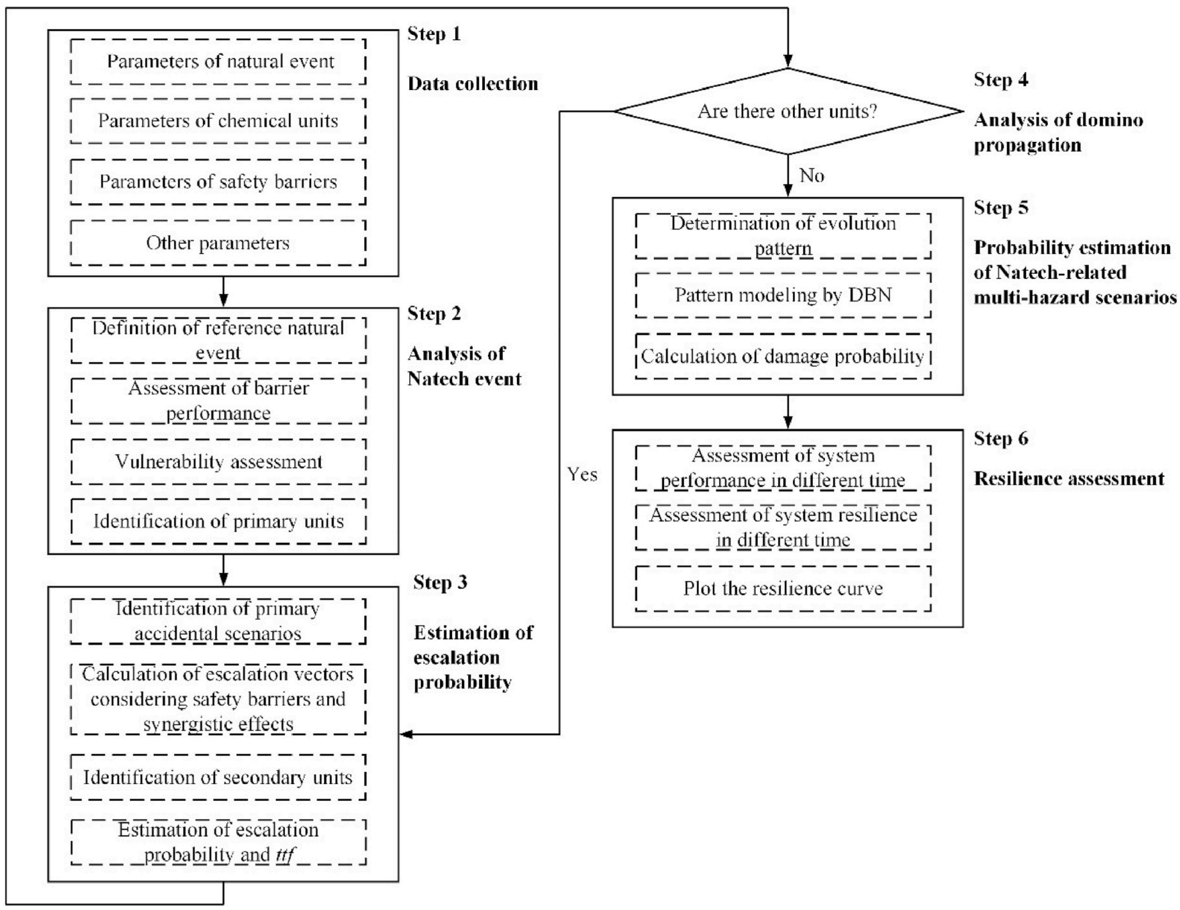


Fig. 4. Procedure of resilience assessment for system in Natech-related cascading multi-hazard scenarios.

iv) other parameters related to accident evolution, like meteorological parameters that affect the intensity of escalation vectors.

Step 2. According to the reference natural event that may affect the concerned area, possible damage of chemical units and degradation of safety barriers should be analyzed. The damage probabilities of chemical units to some natural events can be estimated using the vulnerability model (some available equipment vulnerability models subjected to different natural hazards are summarized in supplementary material). The parameters for barrier performances in the case of a reference natural event could be modified using Eq. (2). Based on the vulnerability results, the units with high damaged probabilities are identified as possible primary units.

Step 3. According to the properties of chemical materials and the ignition mode, primary accident scenarios can be analyzed using an event tree (Necci et al., 2016; Vílchez et al., 2011). Although the natural hazard may have influences on the forming conditions and/or consequences of primary accident scenarios and even the higher-order technological accidents, general consequence assessment model for Natech-specific scenarios is not available to date (Misuri and Cozzani, 2021). The detailed consequence analysis of a Natech event through experiments or simulations is very complex and time-consuming, which is out of scope of our study. Therefore, a simplified assumption (neglecting those influences of natural hazards on accident scenarios) is given, thus the current practice conventional consequence assessment is adopted in this study. In other words, the intensity of escalation vectors transmitted by primary accidents to the nearby units can be estimated using current well-established empirical formulas or consequence assessment software. However, the actual intensity of escalation vectors on a target unit should be modified according to the state of the safety barriers in place. In the calculation of escalation vectors, it is noted that synergistic effects between possible multiple primary units should be considered. Then, the potential secondary units can be identified if the received escalation vectors exceed the threshold from Table 2. The *ttf* and escalation probability of secondary units can be estimated using the probit model.

Step 4. Given that secondary accidents happened, Step 3 is repeated to identify potential tertiary units by substituting secondary units for primary units. Accordingly, the higher-order units may be identified until all units involved in accidents or the escalation vectors are not sufficient to trigger further propagation. Then, the likely pattern of accident evolution is identified.

Step 5. After determining the evolution pattern, the natural events and chemical units are assigned to nodes in a DBN to estimate the damage probabilities of units in multi-hazard scenarios. In DBN, those nodes are connected by directed arcs. Each node would be assigned with a conditional probability table (CPT) to illustrate the conditional dependences or causal relationships between itself and the linked nodes. Through a DBN model, the damage probability of each unit in a different time slice can be obtained. The DBN modeling approach is described in Section 4.2.

Step 6. The system performance drops with different pace in different accident stages, as discussed in Section 3.2. Thus, some discrete points for system performance in different time slices should be determined in order to assess system resilience. In the Natech stage, the potential loss at t_n is only represented by the value of damaged units. Then, the potential loss increases to the whole value of damaged units and their inventories at t_p, the time point when primary fires occur. For the subsequent escalation stage, it is assumed that the domino effect is of the m-order, and the ttf of chemical unit i in the nth-order domino effect is ttf_i^n. After a time period equal to ttf_s^1, time point t_s can be determined. The system performance at time t_p and t_s are the discrete points for the first-order domino effect. Similarly, the time points for higher-order domino effects and corresponding system performance can be calculated. Finally, the system resilience at different time points can be calculated using Eq. (3), and a resilience curve can be depicted by employing the polynomial interpolation of the discrete points

4.2. Implementation of DBN reasoning in accident evolution

Accident escalation is a complex evolution process with temporal and spatial uncertainty, especially in the case of multiple primary accidents due to natural events. DBN is an extension of ordinary BN by introducing temporal dependencies (Kammouh et al., 2020; Khakzad, 2015; Khakzad et al., 2017a; Zinetullina et al., 2021). The node pointed to by the arc is called a 'child node', whereas the node from which the arc depart is called a 'parent node' (Khakzad et al., 2017a). Since DBN is a dynamic probability graph, the probability updating in different time slices can account for time-dependent behavior, which is aligned with the time-dependent aspect of the resilience concept. The timeline is divided into a series of time slices in DBN. A node at the t-th time slice (denotes X_i^t) can be conditionally dependent not only on its parent nodes at the same time slice, but also on the state of itself and its parent nodes at the previous time slices (e.g., t-1-th time slice). The joint probability distribution in DBN can be calculated as (Zinetullina et al., 2021):

$$P(X_1{}^t, X_2{}^t, \cdots, X_n{}^t) = \prod_{i=1}^{n} P\left(X_i{}^t \middle| X_i{}^{t-1}, Pa(X_i{}^t), Pa\left(X_i{}^{t-1}\right), Pa\left(X_i{}^{t-2}\right), \cdots, Pa\left(X_i{}^0\right)\right) \tag{5}$$

where X_i^{t-1} represents the state of X_i^t at the t-1-th time slice; and $Pa(X_i^t)$, $Pa(X_i^{t-1})$, $Pa(X_i^{t-2})$, …, $Pa(X_i^0)$ are the parent nodes of X_i^t at the t-th, t-1-th, t-2-th, 0-th time slice, respectively.

For illustrative purposes, a simplified case of Natech-related cascading multi-hazard scenario involving first-order accident escalation is given, i.e., a natural event directly damaged unit 1 (U1) and has negative effects on the safety barriers of unit 2 (U2), then the accident of U1 impacts U2 leading to the escalation. In view of the propagation pattern, the natural event is assigned as the first node in DBN, its CPT is shown in Table 4.

The natural event would directly damage U1 in a short time, and therefore the nodes representing safety barriers of U1 can be neglected. The CPT of U1 is shown in Table 5. Considering the delayed effect in fire escalation, U2 has an accident probability when the received heat radiation exceeds the threshold for a period longer than the ttf of U2. Thus, for the secondary unit U2, its state at time slice t depends on not only its previous state, but also on the primary accident at the prior time slice t-1 and on available safety barriers at the same time slice. The CPT of U2 is shown in Table 6.

5. Case study

5.1. Case study definition

For illustrative purposes, the applicability and the potential of the methodology are demonstrated via an illustrative tank farm. The tank farm includes 5 same-sized atmospheric tanks, and the layout of the tank farm is shown in Fig. 5. Each tank has a diameter of 37 m and a height of 26 m, with the volume of 25000 m^3; other parameters are listed in Table 7. The meteorological conditions are set as follows: wind flows from the northwest with a speed of 2.7 m/s, stability class is B, the relative humidity is 0.67, and the ambient temperature is 22.5 °C. A Natech-related cascading multi-hazard scenario in the tank farm is assumed as domino effects are triggered by a flood. The flood reference scenario concerns a typical 'high-water condition' which refers to Khakzad and Van Gelder (2017). The flood velocity is assumed to be 0.25 m/s, and the flood height is 3.7 m. For the sake of simplicity, only one accident scenario (pool fire) for the tanks, and water deluge system and fireproofing were selected as the safety barriers to investigate the system resilience. The reference values of barrier parameters in Table 3 are adopted in the case study, and the value of PFD and η of different safety barriers can be calculated by Eq. (2). Given that the leak hole leakage aperture is set to 100 mm, for the tanks that would be involved in the domino chains, the magnitude of heat radiation is calculated by the multi-functional consequence analysis software Phast 8.21 (DNV, 2022). Considering the possible synergistic effects of escalation vectors in the cascading multi-hazard scenario, the values of heat radiation higher than 10 kW/m^2 are listed in Table 8.

The filling degree is a key parameter for vulnerability assessment of atmospheric tanks subject to floods. Several equipment-specific vulnerability models were developed to simplify the relationship between damage probability and filling degree (Antonioni et al., 2015; Landucci et al., 2012; Yang et al., 2020; Zeng et al., 2021). The damage probabilities of chemical units due to flood are assessed by adopting the vulnerability curve (Fig. 6) from literature (Zeng et al., 2021). The damage probability of T1 is 0.948 and of T3 is 0.509. For other tanks

Table 4
Conditional probability table for natural event.

Natural event	Probability
Occur	1
Not occur	0

Table 5
Conditional probability table for U1. (P_0 is the vulnerability of U1 to the natural event).

U1↓Natural event→	Occur	Not occur
Safe	1 - P_0	1
Damaged	P_0	0

Table 6
Conditional probability table for U2 at time slice t. (P_1 is the escalation probability of U2 under the protection of a safety barrier; P_2 is the escalation probability of U2 without the protection of a safety barrier).

U1 (t-1)	S				A			
Safety barrier(t)	Av		Un		Av		Un	
U2 (t)↓U2 (t-1)→	S	A	S	A	S	A	S	A
S	1	1	1	1	1-P_1	0	1-P_2	0
A	0	0	0	0	P_1	1	P_2	1

Label 'S' and 'A' represent the safety state and the accident state of a unit, respectively; Label 'Av' and 'Un' represent the available and unavailable state of a safety barrier, respectively.

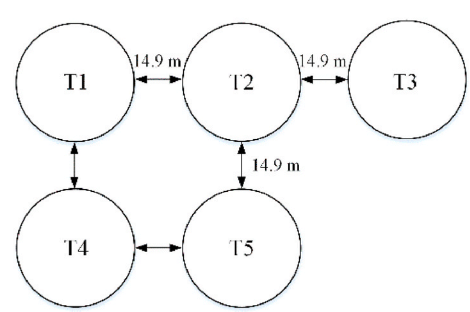


Fig. 5. The layout of an illustrative tank farm.

Table 7
The characteristics of tanks. (The value of diesel oil obtained from the market price of 6230 yuan/m^3 (Cngold.org, 2021)).

Number	Inventory	Filling degree	v_i (yuan)	u_i (yuan)
T1	Diesel oil	10%	12 million	15.575 million
T2	Diesel oil	60%	12 million	93.45 million
T3	Diesel oil	15%	12 million	23.3625 million
T4	Diesel oil	55%	12 million	85.6625 million
T5	Diesel oil	70%	12 million	109.025 million

Table 8
Heat radiation (kW/m2) received by the different tanks (Ti fire).

Ti→/Tj↓	T1	T2	T3	T4	T5
T1	/	20	/	18	/
T2	20	/	20	/	18
T3	/	20	/	/	/
T4	20	/	/	/	20
T5	/	20	/	20	/

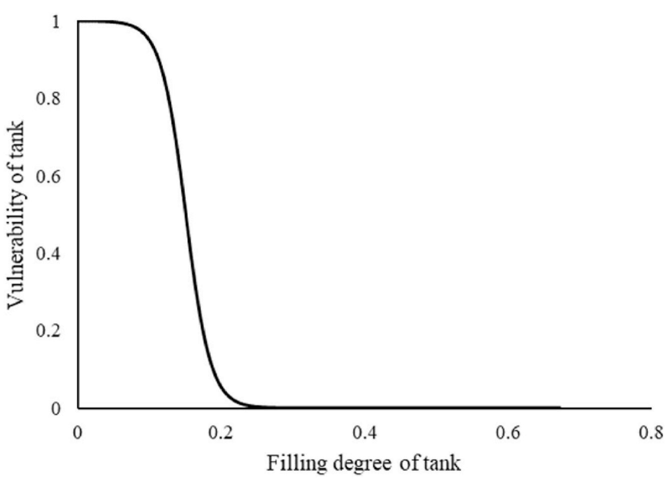


Fig. 6. Vulnerability curve of tank in the case study. (Referred to Zeng et al. (2021)).

with high-level filling of liquid, the damage probability is lower than 10^{-10}. Thus, T1 and T3 are identified as the possible primary units due to their high damage probabilities. To perform the dynamic analysis of accident evolution, it is assumed that the released chemical substances would be ignited in 10 min after the damage of tanks due to the flood. A conservative value of 0.5 for the intensity reduction factor (α) is selected for the water deluge system and a further time ($\triangle t$) of 70 min is considered for the fireproofing, on the basis of Landucci's work (Landucci et al., 2015). Several demonstrative cases are defined to discuss the effect of safety barriers on system resilience.

Case 1 . There are no safety barriers applied in the tank farm;
Case 2 . The water deluge system is used in the tank farm;
Case 3 . Fireproof material is used for coating each tank of the tank farm;
Case 4 . The water deluge system and fireproofing protection are both used in the tank farm.

In practical terms, the performance of fireproof coating would exhibit a temporal degradation under heat radiation. In order to account for the degradation phenomena of fireproofing, it is assumed that the fireproof coating would be ineffective when the exposure time of a fireproofed tank is higher than $\triangle t$.

5.2. Results

For resilience assessment in the case study, the time when the flood impacts the tank farm is considered at zero minute ($t = 0$). Before the time point at 0, the tank farm has its full performance and resilience. The first case represents the worst situation in which no safety barrier is available to impede the escalation of accidents. In this case, the tank farm achieves the lowest system performance to the disruptive Natech-related cascading multi-hazard scenario. The lowest system performance in case 1 is a baseline for resilience assessment, and other cases are discussed to explore the relative efficiency of the safety barriers in improving system resilience.

The temporal and spatial evolution of the Natech-related cascading multi-hazard scenario has been modeled and analyzed using DBN. The DBN models for those four cases are developed as shown in Fig. 7, and the temporal probability inference is performed using the Bayesian network software GeNIe (Bayesfusion, 2022) for a time domain of 100 min and a time step of 10 min. The auxiliary nodes T1′ and T3’ are added in the DBN to articulate the delayed ignition of the damaged tanks in the flood Natech event. It should be noted that the natural event is the main failure cause to safety barriers, resulting in a significant increment in the failure probability of safety barriers. For the sake of simplicity, the random failure of a safety barrier due to internal causes in the cascading multi-hazard scenario is not considered in the case study. Moreover, a temporal arc is drawn from the node of the previous accident unit to the fireproof coating node to describe the performance degradation of fireproof coating exposed to a fire more than 70 min.

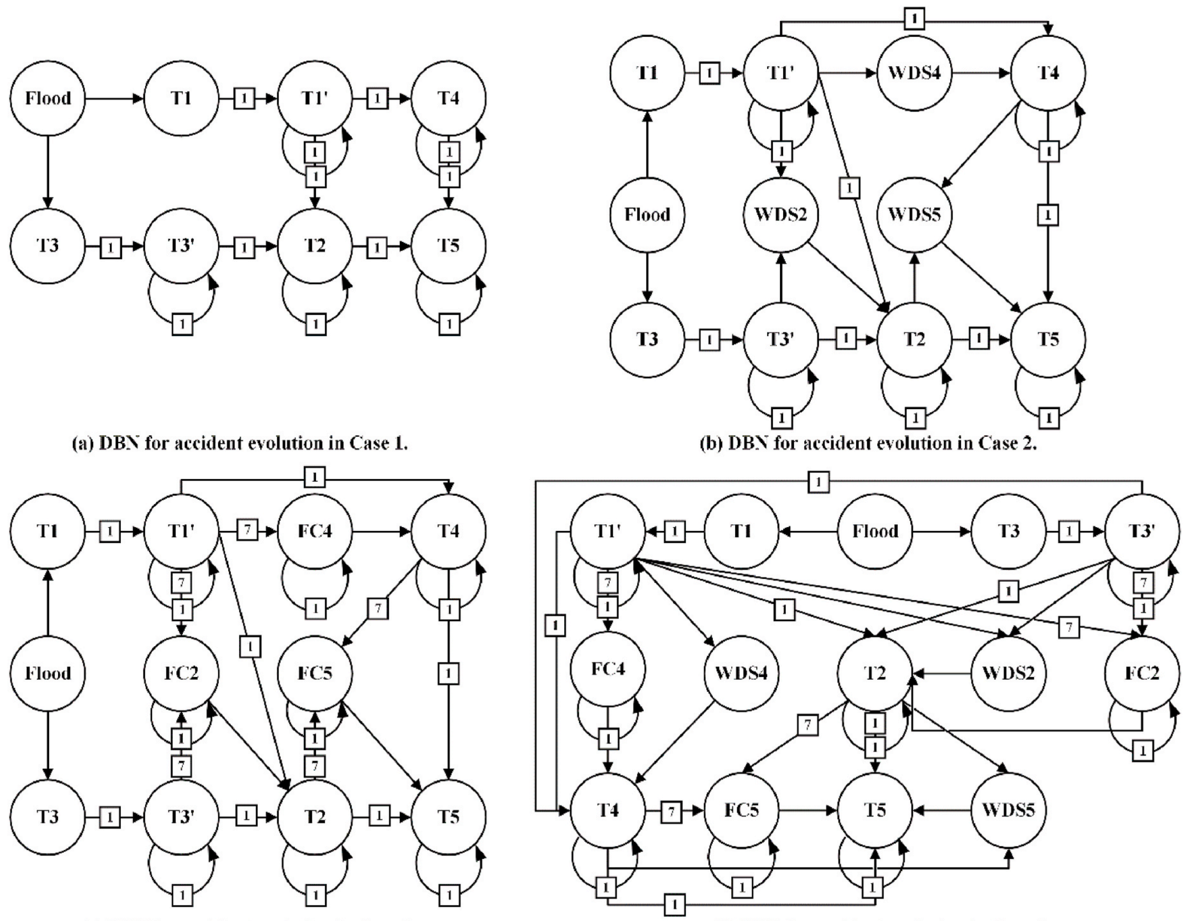
The temporal variation of the fire probability of different tanks is depicted in Fig. 8. Having the fire probabilities of tanks in each time step, the values of φ and R can be calculated. Take case 1 as an example, the pattern of system performance is shown in Fig. 9. The same procedure for the calculation of resilience can be followed for other cases. The resilience curves for all four cases are depicted in Fig. 10 to be able to make a comparison of system resilience in those cases.

Fig. 9 shows that the system performance starts at its original value (1), then it decreases rapidly to reach a lower stable state. The lowest value of φ is 0.0797. The result is not a surprise and is even to be expected since the flood and cascading fires are negative impacts, triggering a rapid propagation of accidents in the tank farm. As time passes, more units may get involved in Natech-related cascading multi-hazard scenarios, leading to the dropping of system performance.

Fig. 10 shows that as the time gets longer, the R value in all four cases decreases. The resilience curve for the evaluation horizon (Time) less than 10 min of all four cases overlap, due to the same initial condition for resilience assessment before the multiple primary accidents that occur at 10 min, either in the presence or in the absence of safety barriers. The enlargement of the area under the resilience curve in Fig. 10 reveals that safety barriers have positive effects on system resilience in the escalation phase. The changing trend of R value in each case, on the time domain from 10 min to 100 min, is different from each other due to the difference of protection performance of single safety barriers or combined barriers. Comparing the resilience curve for case 2 with the curve for case 3 in Fig. 10, it can be concluded that: i) before 77.71 min (an approximate value), the effect of fireproof material on improving system resilience is better than the water deluge system; ii) in the rest of the evaluated time domain, the enhancing resilience effect of water deluge system is better than the fireproof material. This is because passive fireproofing can provide high-performance protection but it would be degraded during fire exposure. Finally, compared with the single safety barrier, the combination of active and passive barriers is a promising route to further improve resilience, as evidenced in Fig. 10.

5.3. Discussion

The case study focuses on flood-related cascading multi-hazard scenarios, since the flood is a significant cause of Natech events and the



(a) DBN for accident evolution in Case 1.
(b) DBN for accident evolution in Case 2.
(c) DBN for accident evolution in Case 3.
(d) DBN for accident evolution in Case 4.

Fig. 7. DBN to model accident evolution in different cases. (WDSi means the water deluge system of unit i, FCi means the fireproof coating of unit i).

basic data for resilience assessment are available in the dedicated literature, but the proposed methodology can be extended to other natural hazards. Besides, real multi-hazard scenarios are more complex than the case study, since more units and safety barriers would be involved and the intensity of the natural event may change dramatically with time and space evolution. Moreover, natural hazards may affect the ignition conditions, the burning behavior of fires, etc., thus the development of ad-hoc models for the consequence assessment of Natech-specific scenarios still is required in the future. The integration of those ad-hoc models could advance the proposed method. However, on the basis of our case study, some interesting issues emerged.

In all analyzed cases, the system performance would be degraded with the accident evolution and the resilience drops accordingly. The system takes advantage of a water deluge system (active barrier) and fireproof coating (passive barrier). The results show that safety barriers can effectively decrease the performance degradation rate in the Natech-related cascading multi-hazard scenarios, consequently improving the system resilience. Moreover, we found that the fireproof coating has better effects on resilience improvement than the water deluge system in early fire propagation, but the effect of fireproof coating cannot be maintained due to its temporal degradation behavior in fire scenarios. The combination of active and passive barriers results in a higher performance on resilience improvement than a single safety barrier, and a cost-effective allocation of combined barriers can make the chemical industrial areas more resilient.

For Natech-related cascading multi-hazard scenarios, a series of disruptive events would successively occur in a short time interval (several minutes or hours). Therefore, some intervention measures are needed to resist the damage of disruptive events and reduce the loss of system performance. The lower performance loss could shorten the recovery phase, the detailed recovery plan and related performance rise can be discussed in the future. The safety barrier conceptualization that is employed in the process industry is focused on the prevention or mitigation of technological accidents. However, as Misuri et al. (2020b, 2021) emphasized, the performance of safety barriers may be depleted due to natural events, leading to unsatisfied protection and mitigation effects. More robust safety barriers in natural events should be developed, which may enhance the resilience of chemical plants to the Natech-related cascading multi-hazard scenarios.

6. Conclusions

In this paper, a methodology to evaluate the trend of resilience of chemical industrial areas during Natech-related cascading multi-hazards is developed. This methodology integrates the relationship of cascading multi-hazards, the role and performance change of safety barriers, the pattern and uncertainties of accident evolution, and performance state transition, allowing a detailed analysis for system performance and resilience considering both probabilistic and temporal terms. The application of the methodology is illustrated through a case study of an illustrative tank farm in the Natech-related cascading multi-hazard scenarios triggered by a flood. The results clearly show the positive effects of safety barriers on system resilience, further evidencing the superiority of combined safety barriers. Moreover, the temporal change of system resilience related to different configurations of safety barriers can be captured through the resilience curves. Although fireproof material shows better effects of resilience enhancement than a water deluge system in the early stage of accident evolution, it is more

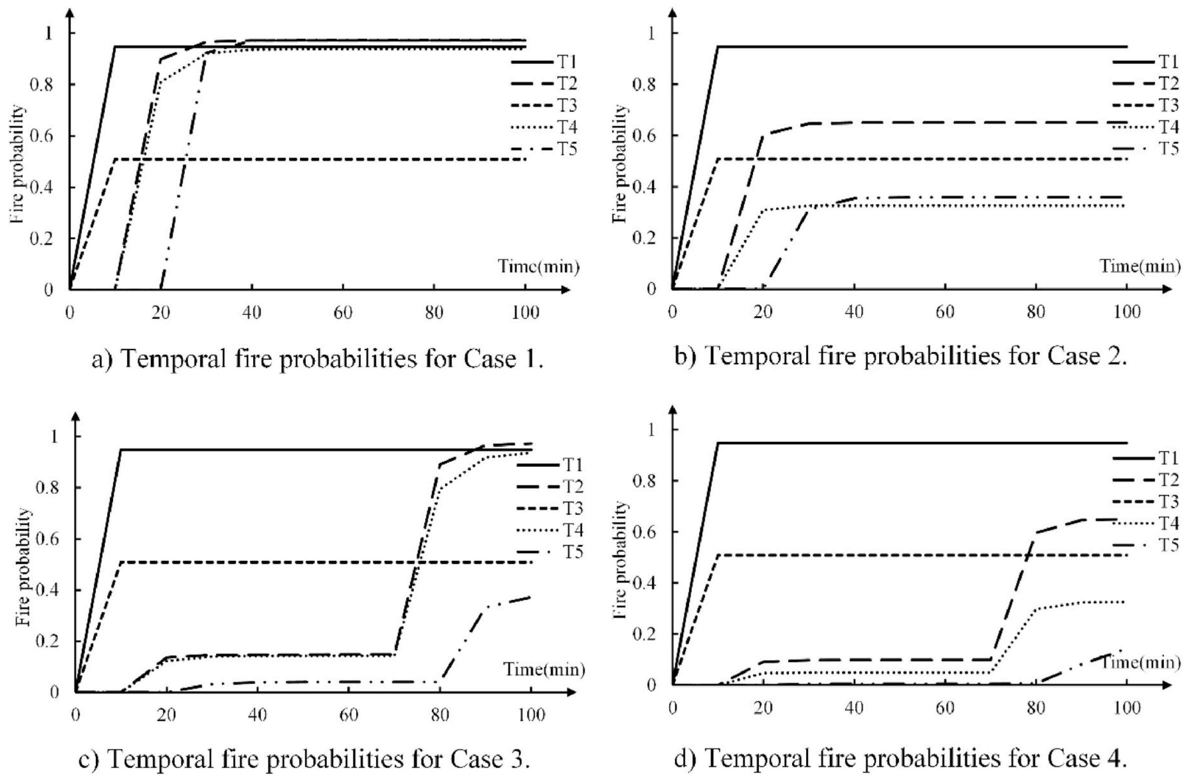


Fig. 8. Temporal evolution of fire probabilities for each tank in Natech-related cascading multi-hazard scenario triggered by a flood.

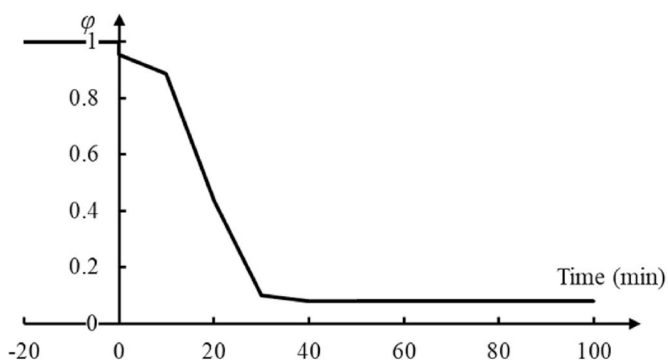


Fig. 9. The performance of the tank farm in Natech-related cascading multi-hazard scenario triggered by a flood (Case 1).

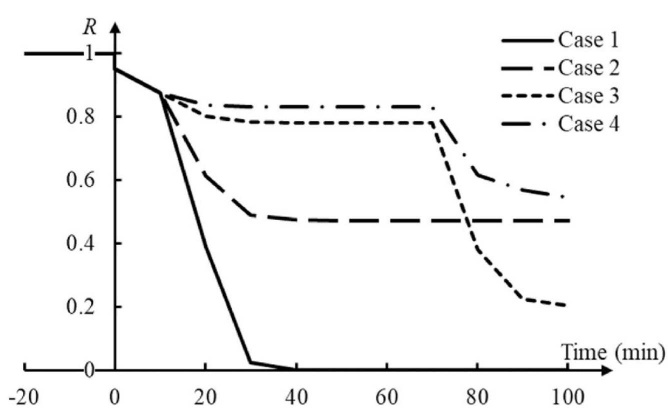


Fig. 10. Comparison of system resilience in different cases.

sensitive to time due to performance degradation. The methodology can be easily applied to the cascading scenarios triggered by other natural hazards by changing the corresponding vulnerability model and performance modification factors of safety barriers. Insights gained by performing the resilience studies could support the optimization of safety barriers with the aim of making chemical industrial areas more resilient during Natech-related cascading multi-hazard scenarios. The proposed method is formulated under the simplified hypothesis that the influence of natural hazards on the evolution of natural-event-induced fire domino effects is neglected. The method can be further extended in the future to include other types of industrial accidents and can be improved by integrating the ad-hoc consequence assessment models of specific Natech scenarios.

Author contribution statement

Tao Zeng: Conceptualization, Methodology, Writing – original draft, Writing – review & editing; Guohua Chen: Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition; Genserik Reniers: Conceptualization, Methodology, Writing – review & editing; Kun Hu: Conceptualization, Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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