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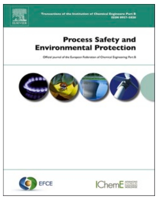

Developing a barrier management framework for dealing with Natech domino effects and increasing chemical cluster resilience

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ABSTRACT

A domino effect triggered by a natural event (a so-called Natech domino effect) represents a typical high-impact low-probability (HILP) event, which may lead to catastrophic consequences. The presence of safety barriers could have an impact on the effects by impeding propagation patterns and mitigating potential consequences. However, coordinating and maintaining safety measures to establish an effective barrier system against Natech domino effects is complicated. In this paper, the concept of what constitutes a safety barrier and the principles of barrier management are reviewed. Subsequently, the complex phenomenon of Natech domino effects is studied at the individual installation level, while the propagation pattern is explored at the system level. The application of safety barriers is discussed with the aim of coping with potential Natech domino effects. A systematic framework of barrier management is developed to establish and improve the barrier system in the whole cycle (design & construction, operation, accident, recovery & improvement) of a chemical industrial area. The challenges are discussed to highlight future study needs.

1. Introduction

The process industry plays an important role in the global economy, and many chemical plants are present worldwide (Chen et al., 2020; Khan et al., 2015). Due to the positive effects on economic benefits of scale, industrial chain integration, and environmental benefits, the clustering of chemical companies in so-called chemical industrial parks (CIPs) is a well-known phenomenon (Chen et al., 2020; Reniers et al., 2018). As a result, there are large inventories of hazardous materials in CIPs, resulting in systemic risks that should not be neglected. In addition to possible chemical accidents triggered by some conventional causes (e.g., mechanical failure and human errors), accidents due to the impact of natural events and accident propagation from nearby units may also happen. Specifically, technological accidents triggered by natural events, referred to as 'Natech events' (Reniers et al., 2018). Domino effects represent an escalation phenomenon of primary accident propagating to nearby installations (Chen et al., 2020). Many studies of accident surveys and statistics (Cozzani et al., 2010; Darbra et al., 2010; Krausmann et al., 2011; Ricci et al., 2021) show possible extreme consequences of Natech events and domino effects. If those two severe accident types are coupled, i.e., domino effects triggered by natural events ('Natech domino effects'), a more complex and rapid accident evolution might occur, resulting in disastrous consequences.

Safety barriers are usually regarded as physical and non-physical measures to prevent, mitigate or control damage of assets exposed to accidents (Liu, 2020; Yuan et al., 2022). Many terms, like protection layers, defenses, risk reduction measures, safety critical elements, safety instrumented systems, etc., are used to describe safety barriers as a safety measure to reduce or eliminate risks (IEC 61511, 2003; Janssens et al., 2015; Liu, 2020; Yuan et al., 2022). CCPS developed the method of layer of protection analysis (LOPA) as a simplified form of quantitative risk assessment (QRA), in which an 'onion' model with several skins is depicted for preventing major accidents in the process industry (Gowland, 2006). The ARAMIS project further emphasized that the failure probability of safety functions needs to be considered in the frequency assessment of accident scenarios (de Dianous and Fievez, 2006; Gowland, 2006). In the ARAMIS project, four categories of safety barriers are defined, including passive barriers, active barriers, human actions, and

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symbolic barriers (de Dianous and Fievez, 2006). Considering the operation attribute, Markowski and Kotynia (2011) re-constructed safety layers, including prevention layer (good engineering practice and basic process control systems), protection layer (safety instrumented systems), and mitigation layer (automatic deluge system and fire brigade). However, those early concepts and methods related to safety barriers mainly focused on how to reduce the probability or scope of a single accident, while the performance and configuration for preventing and/or mitigating cascading accidents are not considered.

In the field of domino effects, safety barriers are used to prevent and mitigate the escalation of accidents. Based on LOPA and the ARAMIS project, Landucci et al. (2015) identified three types of safety barriers, i.e., active protection systems, passive protection systems, and procedural and emergency measures, to prevent accident propagation in fire-related domino effects. A performance assessment method for safety barriers was proposed. Based on the study of Landucci et al. (2015), Khakzad et al. (2017) investigated and modeled the complex evolution of fire-related domino effects in the presence of safety barriers using Dynamic Bayesian Network (DBN) as an approach. Safety instrumented system can be regarded as an active barrier, which consists of sensors, logic solvers and final control elements (Liu, 2020; Xie et al., 2021; Yuan et al., 2022). Xie et al. (2021) proposed a method to analyze the influence of safety instrumented system's performance on the mitigation of cascading failures, and the method is applied to an illustrative case to mitigate failure and fire propagation. For explosion-related domino effects, only passive protections have been considered effective since fast-evolving scenarios limit the application of active barriers and procedural measures. Tugnoli et al. (2013) pointed out that passive barriers such as blast walls and mounds could partially reduce the overpressure and impulse on target units, resulting in less severe escalation scenarios. Sun et al. (2017) investigated the effect of barrier net intercepting fragments using Monte-Carlo simulations, and the results show that domino risks were reduced by 70–90 %. Chen et al. (2021b) studied the performance of protection layers around storage tank against fragments, using numerical simulation. The damage of the tank wall due to fragment impacts has been mitigated since the kinetic energy of fragments has been absorbed by the protection layers. Scientifically combining those safety barriers could make the chemical industrial area safer.

Employing safety barriers to prevent major accidents in the process industry is a complex task, encompassing many factors, such as the limitation of cost and space, prevention and mitigation effects of safety barriers, degradation of barrier performance, and what have you. The Norwegian Petroleum Safety Authority (PSA) defined "barrier management'' as 'coordinated activities to establish and maintain barriers so that they can always maintain their functions', regarding it as an integral part of risk and safety management (PSA – Petroleum Safety Authority Norway, 2013; Johansen and Rausand, 2015). Some studies have made contributions to barrier management considering possible domino effects. For example, Janssens et al. (2015) developed a decision model to locate safety barriers with a limited budget, aiming to maximize the time to failure of target units exposed to fire. Khakzad et al. (2018) discussed the cost-effective allocation of active and passive barriers to mitigate fire-related domino effects. Jung and Lee (2019) determined the optimal location of blast walls using particle swarm optimization to minimize the potential loss generated by possible vapor cloud explosions (VCEs). de Lira-Flores et al. (2019) proposed an optimization algorithm for plant layout to balance domino risk and construction cost through the design of safety instrumented system. Jia et al. (2017) proposed a five-level hierarchical framework for pre-control of domino effects, in which different safety barriers are assigned to different levels, to avoid overlap of safety activities. However, most of previous studies focused on preventing or mitigating fire escalation by employing some typical active and passive barriers, but how to scientifically organize all types of safety barriers for cascading accidents is still hard. In particular, any Natech domino effect is characterized by a fast accident evolution, raising great challenges to barrier management.

The purpose of this paper is developing a holistic framework for barrier management for dealing with Natech domino effects. The concepts and principles related to barrier management are discussed. Moreover, the basic elements and evolution pattern of Natech domino effects are explored, which allows organizing and allocating proper safety barriers to prevent and mitigate a potential accident evolution. Finally, the implementation of the developed framework in the whole cycle of a chemical industrial area is illustrated and the challenges are further discussed.

This paper is organized as follows. Section 2 reviews the concepts of safety barriers and summarizes the principles of barrier management. In Section 3, the features and evolution process of Natech domino effects are discussed, and a general prevention and mitigation scheme by employing safety barriers is established in form of bow-tie models. Then, a comprehensive framework of barrier management against Natech domino effects is developed in Section 4. Finally, Section 4.4 concludes this paper.

2. Review of barrier management in process industry

2.1. *Basic concept of safety barriers*

An accident may occur only if all the protection layers fail. The concept of safety barriers is further developed, indicating the measures for preventing or mitigating accidents (Gowland, 2006; Liu, 2020; Sklet, 2006; Yuan et al., 2022). However, there is still no acknowledged and generally accepted definition of what is exactly a safety barrier. Some typical definitions and classifications of safety barriers in different studies are listed in Table 1.

Table 1 clearly shows that the common feature of any safety barrier is the ability to prevent and mitigate possible accidents, i.e., its safety function to reduce risks. For example, the typical technical barrier, safety instrumented system, could detect dangerous situations and implement some reactions to ensure the control of relevant process equipment (Meng et al., 2018; Zerrouki and Tamrabet, 2015). However, scholars have different ideas about what means should be regarded as safety barriers, resulting in the difference of the barrier concept and its classification. The early definition of safety barriers (de Dianous and Fievez, 2006; Hollnagel, 2008; Sklet, 2006) mainly focuses on prevention and mitigation of a single accident, and eventual extended to the field of domino effects for escalation prevention. Besides, some scholars define several barrier typologies based on the operation types, and others provide different barrier classifications according to the barrier function. Active barriers that require external activations to perform their performance and passive barriers that do not need activations to perform their performance, have been adopted by many studies (Khakzad et al., 2017, 2018; Landucci et al., 2015; Misuri et al., 2020b, 2021a). Inherently safe design is deemed as a passive barrier in the early studies, but it has been excluded in most recent studies since its application is limited to the design stage. In addition, appropriate procedures may provide strong interventions to mitigate accidents, being referred to as procedural barriers (related to operational and organizational factors), also deserve more attention. In this paper, safety barriers are defined as physical and non-physical means to preventing and mitigating accidents and possible escalations within chemical industrial areas in the context of Natech events.

2.2. *Principles for barrier management*

PSA – Petroleum Safety Authority Norway (2013) stated that barrier management aims to establish and maintain barriers to address the accident risk at any given time. It should be an integral part of the facility's health, safety and environmental (HSE) management. PSA – Petroleum Safety Authority Norway (2013) also developed a framework for barrier management based on the process for establishing the risk picture and barriers in the planning, design and construction phase, in which six

Table 1
Overview of safety barrier definitions and classifications.

Authors	Safety barrier definition	Classification
de Dianous and Fievez (2006)	Physical and engineered systems or human actions based on specific procedures or administrative controls, which directly serves the safety function.	i) Passive barriers ii) Activated barriers iii) Human actions iv) Symbolic barriers
Sklet (2006)	Physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents.	i) Passive barrier (including physical barrier and human/ operational barrier) ii) Active barrier (including technical barrier that can be further classified into safety instrumented system, external risk reduction facilities and other technology safety-related system, and human/ operational barrier)
Hollnagel (2008)	Means to carry out the barrier functions for preventing or protecting against the uncontrolled transportation of mass, energy, or information.	i) Physical or material barrier systems ii) Functional barrier systems iii) Symbolic barrier systems iv) Incorporeal barrier systems
Rathnayaka et al. (2011)	Safety measures to prevent, control or mitigate the consequences of an accident process act.	i) Management and organizational barrier ii) Human factor barrier iii) Release prevention barrier iv) Dispersion prevention barrier v) Ignition prevention barrier vi) Escalation prevention barrier vii) Damage control and emergency management barrier
Zerrouki and Tamrabet (2015)	Safety measures to reduce the risks to a tolerable level to avoid the catastrophic accidents.	i) Organizational barriers ii) Technical barriers
Landucci et al. (2015)	Protection system could reduce the likelihood or possibility of domino events.	i) Active protection systems ii) Passive protection systems iii) Procedural and emergency measures
Johansen and Rausand (2015)	A system that has been designed and implemented to perform one or more barrier functions that is designed to prevent or mitigate the consequences of a specific hazardous events.	i) Proactive barriers ii) Reactive barriers
Xie et al. (2018)	Means, such as a technical or physical system, human actions, or procedural deficiencies, to prevent, control or mitigate undesired events or accidents.	i) Barriers against common cause failures ii) Barriers against cascading failures iii) Barriers efficient for both failures
Misuri et al. (2021a)	Physical and non-physical measures intended to prevent, mitigate or control dangerous deviations of the industrial system under analysis or accidents.	i) Passive barriers ii) Active barriers iii) Procedural barriers
Yuan et al. (2022)	A physical or non-physical tool planned to prevent, control, or mitigate undesired events or accidents.	i) Technical barriers ii) Non-technical observable barriers iii) Non-technical non-observable barriers

main works are divided, including: i) determine the context, ii) risk assessment, iii) risk treatment, iv) establish a specific barrier strategy and specific performance standards, v) communication and consultation, and vi) monitoring and review. Some of those works need to be performed repeatedly according to the results of risk treatment and monitoring and review until forming a better barrier strategy for the investigated facility. Pitblado et al. (2016) illustrated the concept of dynamic barrier management, mainly in the operation stage of chemical facilities. Through a combination of inspection, audit, sensors, preventive maintenances, and fault records, the barrier status can be inferred based on real-time information, which is beneficial for the optimization of barrier maintenance. However, Hauge and Øien (2016) pointed out that traditional barrier management focused on the technical barriers, while the importance of operational and organizational barriers is largely neglected. Hosseinnia Davatgar et al. (2021) developed a risk-based approach for barrier management in the oil and gas sector, considering both management factors and technical factors, providing credible results for barrier performance and guiding inspection and maintenance work.

Overall, barrier management is a complicated system engineering problem, involving the selection, combination, optimization, and maintenance of safety barriers. Although scholars and international organizations developed the framework and context of barrier management, most of them mainly focused on a specific phase of the life cycle and on specific types of safety barriers. Therefore, the principles for barrier management should be refined and summarized, as follows:

i) Barrier management of a chemical industrial area is a dynamic process that not only addresses the planning, design and construction phase, but also can be applied to other phases of the life cycle, such as normal operation, accident response, and the recovery phase.
ii) External and internal factors, such as regulations and guidelines, requirements and goals of risk management, design and operation parameters, and technological trends, are the premise conditions for forming the target object of barrier management.
iii) Possible hazard scenarios should be identified that provide a guide for selecting safety barriers and defining the barrier roles.
iv) Risk of the target object needs to be evaluated; and a specific barrier strategy should be developed to ensure that the risk level of the target object is acceptable.
v) Barrier performance should be monitored to achieve an early warning for barrier degradation. Barrier functions can be maintained, even improved, through replacement, repair, or updating.

3. Natech domino effect

3.1. Features and basic elements

As Chen et al. (2020) suggests, a Natech domino effect is a type of domino effect triggered by natural events. Therefore, 'propagation' and 'escalation', as the fundamental features of domino effects (Jia et al., 2017; Reniers and Cozzani, 2013), are features of Natech domino effects. For domino effects in a chemical industrial area, propagation is associated with escalation, finally forming accident chains with serious consequences. Specifically, the propagation usually leads to more units involved in accident sequences, while the escalation results in more severe consequences.

Comparing to the conventional domino effects, i.e., the accident evolution of a single technological accident (fire or explosion), the evolution of Natech domino effects is more complex and the overall consequences are more severe. The main reasons are: i) Natech domino effects involve multi-hazards; ii) multiple chemical units may be damaged simultaneously by the natural hazard, leading to several loss of containment (LOC) events and finally forming a multi-source accident scenario; iii) the multi-source accident scenario could create a fast propagation pattern within the chemical industrial area. Considering the cause and accident sequences of Natech domino effects, nine basic elements are defined for a Natech domino effect, as shown in Table 2.

For the illustrative purpose, a simple Natech domino effect is depicted in Fig. 1, for which a chain of events is connected sequentially. The secondary event is determined by a primary accident, the primary

Table 2
Elements for a Natech domino effect.

Element	Definition
Trigger event	A natural hazard that initiates the accident sequence (e.g., lightning, earthquake, flood, storm, etc.).
Damage vector	The damage effects (e.g., electric arc, ground motion, flood impacting, wind loading, etc.) generated by the trigger event.
Primary event	Failure of a chemical unit and a LOC event due to the impact of the damage vector, which can further evolve to the primary accident.
Evolve factor	A hazardous factor with energy that may due to natural hazard, static electricity, chemical reaction, high-temperature environment, the former-order accidents in domino chain, etc., causing the evolution of a LOC event to an accident (fire or explosion). (e.g., ignition)
Primary accident	A fire or explosion that starts the propagation of technological accidents, triggering one or more secondary event(s).
Secondary event	Failure of a chemical unit and a LOC event, caused by the impact of the escalation vector generated by the primary accident(s).
Escalation vector	The physical effects (heat radiation, overpressure, fragment) generated by the primary accident.
Propagation	The process of more units involved in the accident sequences (spatial propagation); or an unwanted event propagates with a chemical unit (temporal propagation).
Escalation	The intensification of overall consequences.

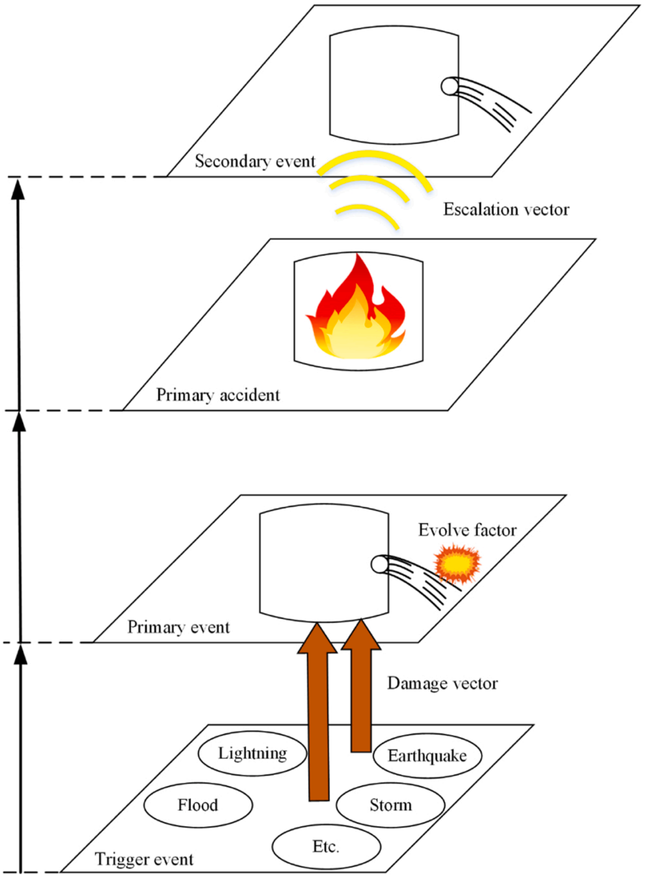

Fig. 1. Example of a Natech domino effect.

accident by a primary event and the primary event by a trigger event. The domino chain begins when a trigger event occurs and ends when a secondary event occurs due to propagation. Each element appears accordingly with the time evolving, resulting in the final outcomes that are an escalation of the primary event.

With respect to natural hazards that may be the trigger event, Ricci et al. (2021) classified 4 macro-categories (geophysical, meteorological, hydrological and climatological) and 12 sub-categories (e.g., earthquake, landslide, storm, lightning, flooding, wildfire, etc.). Based on the statistical analysis of past Natech events, some scholars pointed out that lightning, floods, and storms are among the most frequent natural events that trigger technological accidents, while earthquakes have resulted in the most severe consequences (Cozzani et al., 2010; Krausmann et al., 2011; Ricci et al., 2021). However, some specific types of natural hazards, like lightning, volcanic activity and wildfire, could directly provide an evolve factor, thus the evolution of a primary event to a primary accident is quickly skipped.

3.2. Propagation pattern

The propagation pattern shows the causal relationship existing within an accident evolution. For conventional domino effects, Reniers and Cozzani (2013) classified propagation patterns into three categories, including: i) simple propagation representing a 'one-to-one' correspondence; ii) a multi-level domino chain to extend the accident sequence as the rule of simple propagation; and iii) multi-level propagation involving 'one-to-more' propagation relationship, i.e., a primary accident triggers more than one secondary accident, and secondary accidents trigger several tertiary accidents, and so on. The multi-level propagation is more consistent with the complex evolution of real domino accidents in case of Natech events (Reniers and Cozzani, 2013). Fig. 2 shows the possible multi-level propagation pattern for Natech domino effects.

As an example, Fig. 2(a) shows a possible propagation pattern for lightning-induced Natech domino effects. Lightning-related scenario is a special case since the lightning usually strikes one installation and directly leads to fire or explosion (Necci et al., 2013, 2014, 2016). Thus, a simple triggering relationship, i.e., the lightning triggering a single-source primary accident, is adopted in this case. Subsequently, the primary accident results in several secondary events (parallel effects). For Natech domino effects triggered by other natural events, for instance, earthquake or flood, it is assumed that several (e.g., two) primary events occur in one go due to the trigger event (also a parallel effect), as shown in Fig. 2(b). The primary accidents are formed due to the evolve factors coupled with the primary events. Except for the parallel propagation, several primary accidents may trigger a secondary event through synergistic effects. In general, the parallel effect reflects the escalation capacity of a trigger event or a lower order accident and the synergistic effect is related to potential damage probability of higher-order units.

The analysis of the propagation patterns provides a framework to describe the evolution of Natech domino effects. Specific accident scenarios at damaged units are essential to understand the actual accident propagation. Previous studies provide discussions about possible

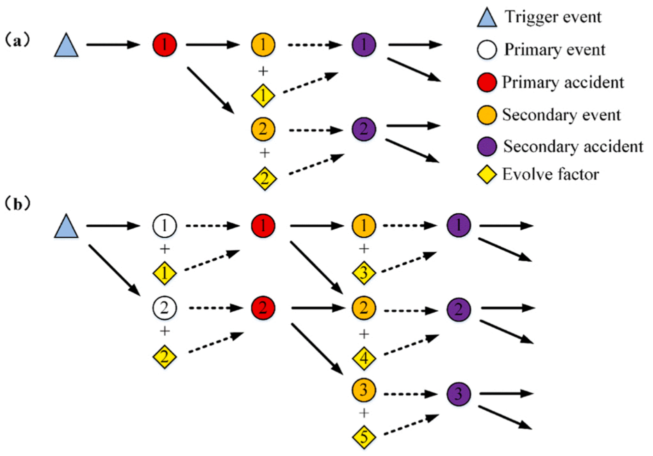

Fig. 2. Example of multi-level propagation pattern for Natech domino effects.

accident scenarios due to natural events (Antonioni et al., 2007; Cozzani et al., 2010; Huang et al., 2020; Necci et al., 2014). Moreover, expected secondary accident scenarios in the context of domino effects are reported in literature (Reniers and Cozzani, 2013; Jia et al., 2017). Accident scenarios related to Natech domino effects have not systematically been summarized. Based on the scenario-related researches of Natech events and domino effects and the discussion of propagation patterns, potential accident scenarios in Natech domino effects are listed in Table 3.

3.3. *Prevention and mitigation*

Prevention and mitigation of domino effects in chemical industrial areas have gained great concern in scientific literature (Chen et al., 2021b; Cozzani and Reniers, 2021; Jia et al., 2017; Landucci et al., 2015; Reniers and Cozzani, 2013). A synthetic and comprehensive set of safety barriers, i.e., a barrier system, may significantly reduce the propagation probabilities, even impede the domino chains. However, the barrier system for conventional domino effects, may be ineffective for Natech domino effects since: i) natural events may trigger multi-source primary accidents; ii) ordinary safety barriers are not able to protect chemical units from the impact of natural events. Considering the features and propagation patterns of Natech domino effects, more or different safety barriers are needed and scientifically allocated to establish an effective barrier system. A conceptual model to allocate safety barriers is developed in the form of a bow-tie diagram (Fig. 3 and Fig. 4). For the sake of simplicity, Fig. 3 and Fig. 4 only mention the propagation from a trigger event to secondary accidents, but the prevention concept derived from the first-level propagation of technological accidents can be applied to any further higher-level propagation.

Fig. 3 shows the conceptual models of barrier allocation for lightning-induced Natech domino effects. Considering the damage mechanisms of lightning to process units, Fig. 3(a) illustrates the direct damage of lightning on an installation containment that is a LOC, may lead to fire. In addition, lightning may cause indirect damage to trigger an explosion through the ignition of flammable vapor mixtures inside process units, as shown in Fig. 3(b) (Necci et al., 2014). Fig. 4 depicts the conceptual model for Natech domino effects triggered by earthquake, in which possible multi-source primary accidents are considered. Each conceptual model can be divided into two bow-tie structures. Take Fig. 3 (a) as an example, the first bow-tie structure shows the process of a lightning-related Natech event, and the consequences is the primary accident. Another bow-tie structure describes the propagation of accidents, resulting in the occurrence of secondary accidents. Four safety functions for safety barriers are identified according to their place in the bow-tie structures: 1) on the left-hand side of the first bow-tie: protecting chemical units from the impact of a natural event (safety function 1); 2) on the right-hand side of the first bow-tie: decreasing the occurrence possibility of a primary accident (safety function 2); 3) on the left-hand side of the second bow-tie: reducing the strength of escalation vectors received by a target unit (safety function 3); and 4) on the right-hand side of the second bow-tie: decreasing the probability of a secondary accident (safety function 4). Corresponding safety barriers with different safety functions are discussed in detail.

i) Safety barriers with safety function 1

Natural events usually are hard to predict and could pose a huge impact on chemical units in a short time. Passive barriers are more effective and reliable, and the application of active barriers and procedural barriers may be impossible since their acting need extra response time. Specifically, to achieve the protection goal, safety barriers can be designed from two aspects: i) avoiding that damage vectors directly contact with chemical units; ii) reducing the strength of damage vectors received by chemical units so that the chemical units can resist the damage effects. The former one is usually applied for lightning-related and flood-related scenarios, such as the tank shunts, lightning conductors, and circuit breakers for lightning-related scenarios (Krausmann et al., 2011), and earthen berms and concrete walls for flood-related scenarios (Krausmann et al., 2016). The latter one is more suitable for earthquake-related, flood-related, and storm-related scenarios, like seismic reduction and isolation systems, and anchoring and restrain systems (it can be applied to all mentioned scenarios to reduce the loading on chemical units), etc. (Krausmann et al., 2011, 2016).

ii) Safety barriers with safety function 2

Safety barriers with safety function 2 have been paid more attention in practice, which is more in accordance with the early

Table 3

Potential accident scenarios in Natech domino effects. (Some illustrative examples).

Trigger event	Damage vector	Primary event	Primary accident scenario	Escalation vector	Possible secondary accident scenario
Lightning	Electric arc having a high energy density	Ignition of confined material	Pool fire	Heat radiation Fire impingement	Jet fire, pool fire, and BLEVE
			Jet fire	Heat radiation Fire impingement	Jet fire, pool fire, and BLEVE
			Tank fire[*]	Heat radiation	Jet fire, pool fire, and BLEVE
			Confined explosion	Overpressure Fragmentation	All[†]
Earthquake Flood Storm	Ground motion due to earthquake Buoyancy force, hydrostatic and hydrodynamic pressure due to flood Wind pressure and buoyancy force due to storm	LOC	Fireball	Heat radiation Fire impingement	Tank fire
			Flash fire	Fire impingement	Tank fire
			Pool fire	Heat radiation Fire impingement	Jet fire, pool fire, and BLEVE
			Jet fire	Heat radiation Fire impingement	Jet fire, pool fire, and BLEVE
			BLEVE	Fragmentation Overpressure	All[†]
			VCE	Overpressure	All[†]

[*] Tank fire in the case of lightning as a trigger event, should be considered only for tanks having a fixed roof with a weak joint.

[†] All means any of the scenarios including: Pool fire, jet fire, fireball, flash fire, chemical explosion, BLEVE, and VCE.

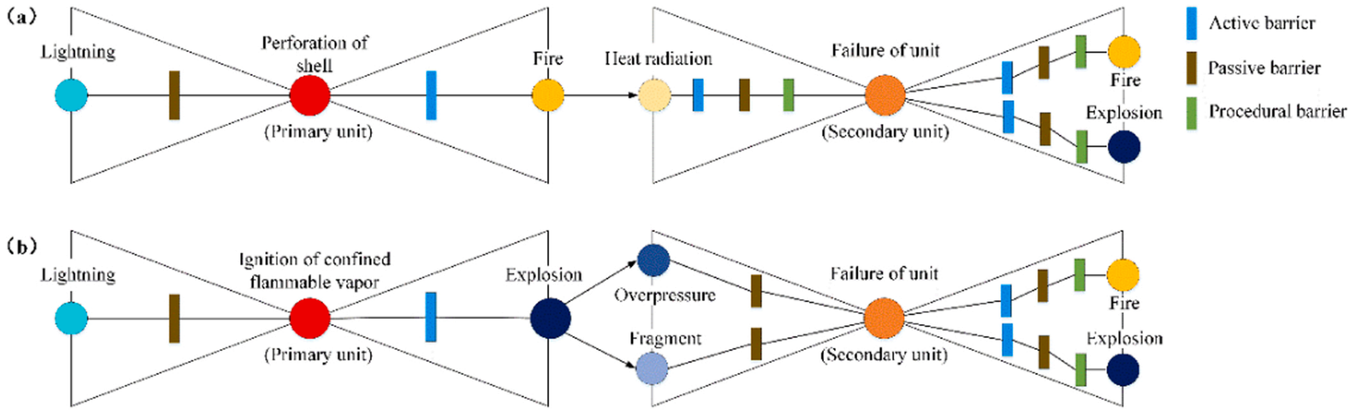

Fig. 3. Conceptual model for barrier allocation against Natech domino effects triggered by lightning. (illustrative).

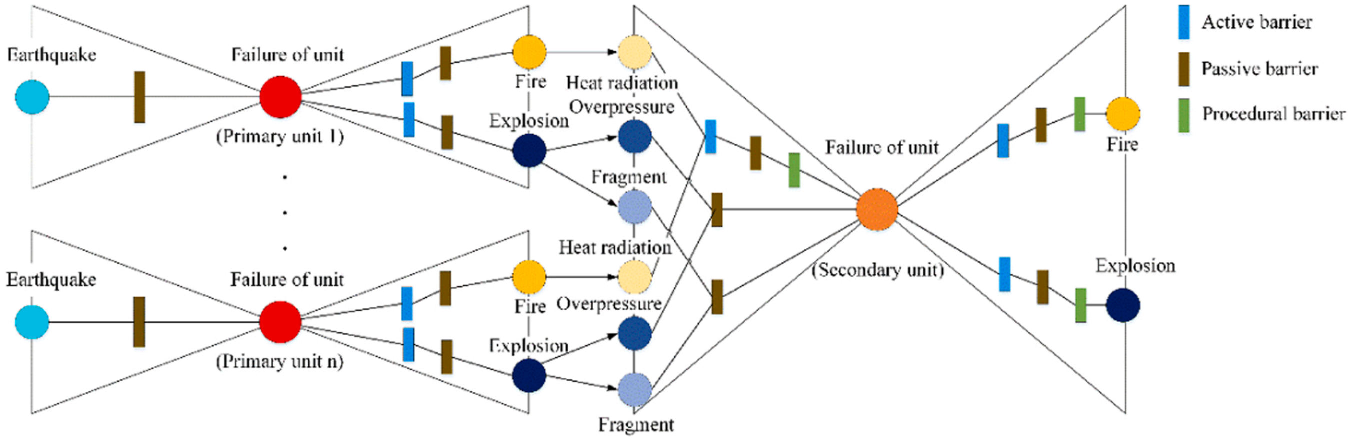

Fig. 4. Conceptual model for barrier allocation against Natech domino effects triggered by earthquake. (illustrative).

concept of safety barriers to prevent minor events evolving to accidents (fire or explosion). Active and passive barriers could both be employed to limit the hazardous environment due to a primary event and/or ignition sources (evolve factors). For example, i) dikes (passive barriers) around chemical units could limit the leakage of chemicals in a certain area, reducing the exposure to an ignition source (Yoo and Lee, 2019); ii) if gas detectors indicate a leakage event, the shut down values (active barrier) would be activated to limit the release of inventories (Ahmad et al., 2013); iii) water spray curtains (active barrier) could dilute hazardous vapor clouds to mitigate an explosive environment (Rana and Mannan, 2010). For the specific case due to lightning strikes, active barriers (fixed foam system, automatic rim-seal fire extinguishing system, Inert-gas blanketing system, etc.) are widely used to eliminate accidents (Necci et al., 2014, 2016). However, procedural barriers in such case are considered unavailable since: i) evacuation is the main objective of internal emergency actions; ii) the response time of mitigation-related emergency procedures is too long to adequately deal with natural hazards.

iii) Safety barriers with safety function 3

Cozzani and Reniers (2021) stated that the mitigation of domino escalation involves the combination of active barriers, passive barriers, and procedural barriers. Active barriers are more widely adopted in fire-related domino effects, especially in the case of pool fires and jet fires related scenarios, to reduce the heat radiation received by secondary units. Passive barriers could be applied in both fire-related and explosion-related domino effects, providing extra protection for secondary targets at any time. For example, fireproofing could directly increase the time to failure of target units to external fires, blast walls could effectively reduce the overpressure acted on the secondary units, blast blankets are an effective solution to mitigate damage due to fragment impacts (Tugnoli et al., 2013). Specifically, passive barriers play a dominant role in the escalation prevention of explosion-related domino effects since the rapid evolution of accidents limits the application of active barriers and procedural barriers (Cozzani and Reniers, 2021). Procedural barriers including procedures and contingency plans to respond for major accident scenarios, usually are regarded as a strong intervention to mitigate primary fires, and may possibly terminate accident sequences.

iv) Safety barriers with safety function 4

In this stage, the role of safety barriers is to avoid a secondary accident, which lies down to preventing the accident of a secondary process unit. In general, this type of safety barriers aims to limit secondary events and evolve factors. Therefore, technical safety barriers with safety function 2, such as dikes and water spray curtains, can be applied in this stage to perform safety function 4. Moreover, procedural barriers may be available to eliminate the risk of hazardous material leakages.

Overall, this section provided a generalized solution to allocate different types of safety barriers with the aim of dealing with Natech domino effects. If the specific safety barriers are given, the bow-tie structure should be modified according to the actual barrier tasks.

4. Barrier management framework coping with Natech domino effects

4.1. Scheme for establishing an effective barrier system

Barrier management is a comprehensive work to coordinate and maintain safety barriers (Johansen and Rausand, 2015; Liu, 2020; PSA – Petroleum Safety Authority Norway, 2013; Yuan et al., 2022), which is reflected in a barrier system. However, although setting some safety barriers within a chemical industrial area, major accidents still may occur. Therefore, the barrier system should be strengthened and improved so as to make the chemical industrial area as safe as possible. Fig. 5 presents a scheme for the establishment and improvement of a barrier system, which clearly shows the path leading to a barrier system, adequate to deal with Natech domino effects.

Many safety regulations and laws are formulated by government agencies, requiring some basic safety barriers and risk acceptance criteria related to a chemical industrial area. As evident in Fig. 5, basic safety barriers need to decrease the risk level of a chemical industrial area to satisfy certain risk acceptance criteria. However, those basic safety barriers are usually used to address major accidents occurring during normal operation of a chemical industrial area, hence the establishment of basic safety barriers cannot guarantee 'full protection' for the chemical industrial area, especially considering possible escalation accidents. Some studies evidenced that the risk level considering Natech domino effects, although accounting for the role of some basic safety barriers, is higher by several orders of magnitude than the conventional case excluding Natech and escalation scenarios (Huang et al., 2020; Misuri et al., 2020a). Therefore, some complementary barriers addressing potential Natech domino effects are needed until the risk level complies with the legal requirements. To this end, an early barrier system is established. The early barrier system can be seen as the set of basic safety barriers and complementary safety barriers, necessary to comply with all rules and regulations.

However, Pitblado et al. (2016) pointed out that risk rises in steps as individual safety barriers (passive or active) degrade, thus some measures, like repairment or introducing some additional equivalent safety barriers, should be carried out to return the risk to the excepted level. Furthermore, the efficiency of procedural barriers could be facilitated through education and training. Setting up specific training programs and providing education for the case of Natech domino effects are both recommended, ensuring an effective response to the special circumstances during Natech events. As a result, an advanced barrier system is established by maintaining the performance of early barrier system and enhancing procedure barriers.

When an accident occurs in a chemical industrial area, obviously a barrier system would be activated to mitigate and control the accident. During the accident, some safety barriers may be damaged or do not perform as expected. After the accident, the chemical industrial area would recover and improve the old barrier system based on the lessons learned from the accident, providing a further improved barrier system for the next accidents.

4.2. Barrier management framework

Starting from the scheme presented in Fig. 5, a comprehensive framework for barrier management in the whole cycle of a chemical industrial area to deal with Natech domino effects is developed in Fig. 6. The whole cycle of a chemical industrial area is divided into four stages, that is: (1) design & construction stage, (2) operation stage, (3) accident stage, and (4) recovery & improvement stage. The implementation and relevant tools of each stage are further discussed in detail.

4.2.1. Design and construction stage

The objective in this stage is establishing an early barrier system to ensure that the chemical industrial area complies with rules and regulations. In this stage, basic information of the chemical industrial area should firstly be collected to identify possible trigger events and to describe the system. Basic information includes:

i) risk map and historical data of natural hazards;
ii) the actual design and condition of the investigated chemical industry area;
iii) characteristics of chemical installations, such as dimensional parameters, categories and properties of involved hazardous substances, etc.;
iv) requirements about safety barriers and risk acceptance criteria in laws, regulations, rules, design standards, etc.;
v) relevant information about the surrounding environment, such as metrological parameters, population density and distribution, etc.

In particular, the specific risk acceptance criteria and guidelines for the chemical industrial area should be determined in accordance with applicable laws and other relevant documents. The risk acceptance criteria provide a basis to judge whether the risk level of the chemical industrial area is acceptance.

Subsequently, basic safety barriers are constructed based on the requirements of regulations, standards, etc. Then, potential Natech domino effects should be analyzed to assess the likelihood of installation failure and to identify the key units in accident evolution, which requires some simplified probability models. In general, many methods are

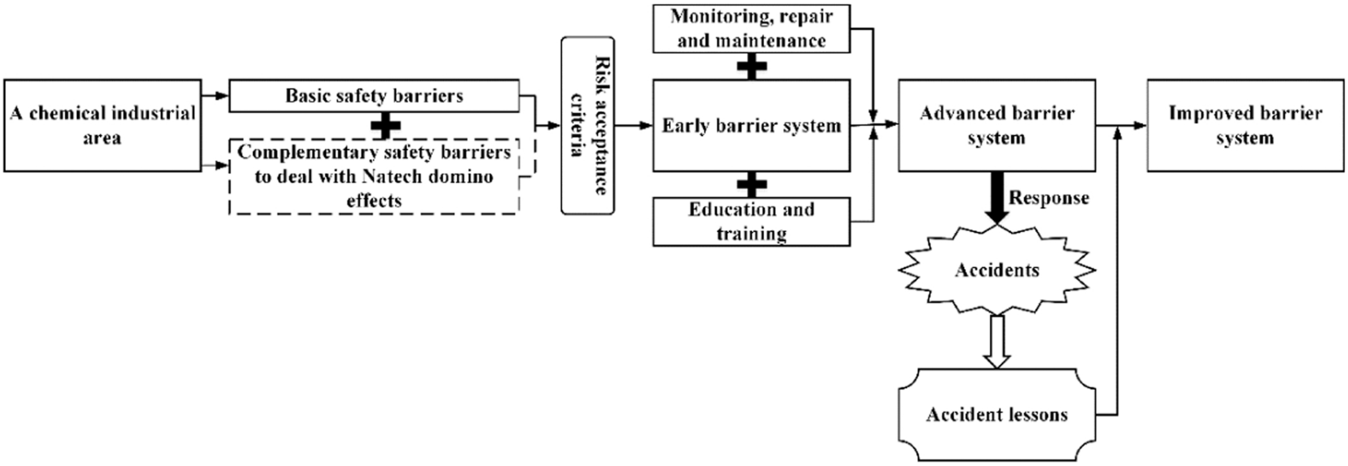

Fig. 5. A scheme for a barrier system, adequate to deal with Natech domino effects.

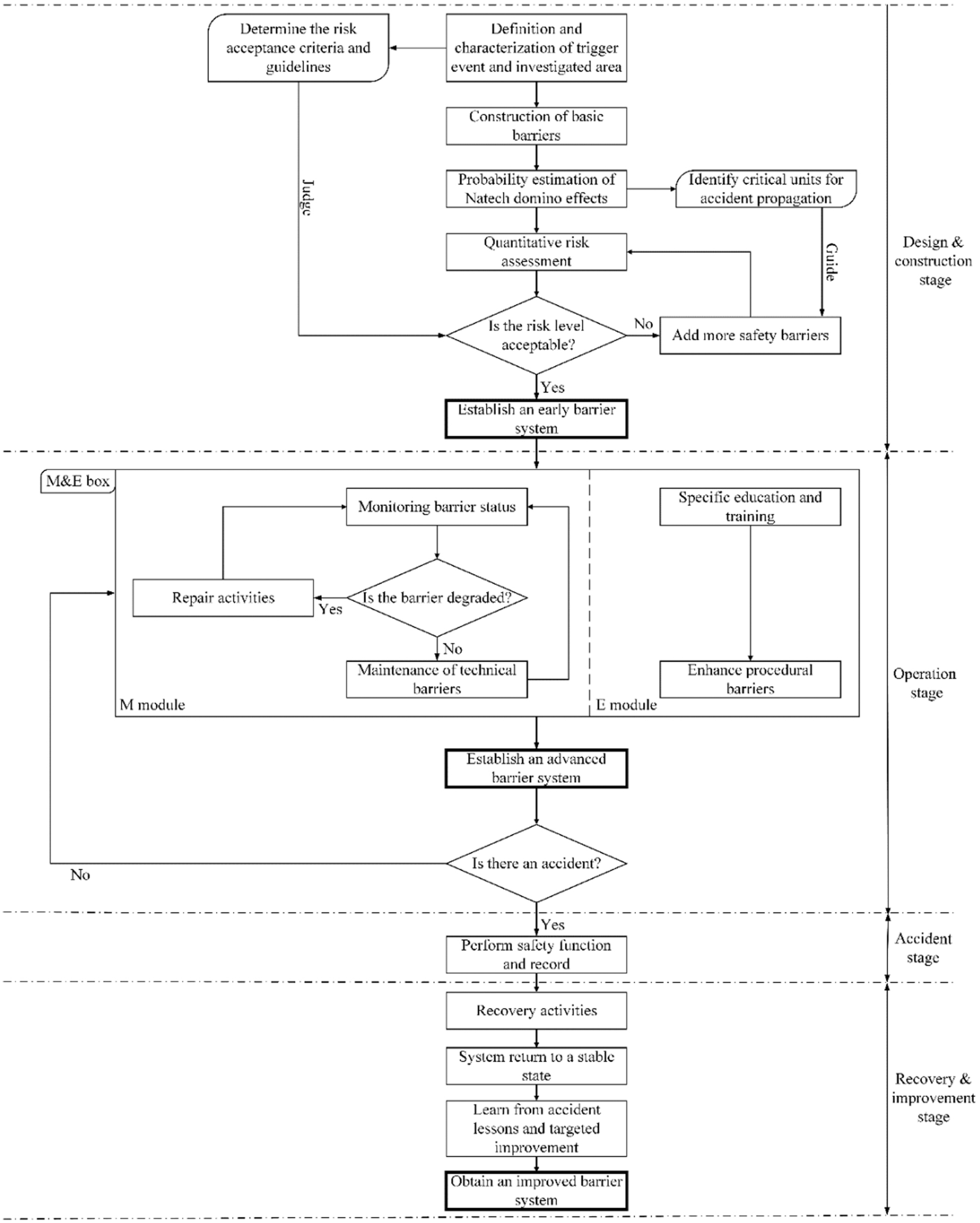

Fig. 6. Barrier management framework for dealing with Natech domino effects.

available in the literature to quantitatively study Natech events or domino effects. For instance, a tank damage probability assessment model related to lightning is developed considering lightning capture and damage mechanisms (Necci et al., 2013, 2014, 2016); probit function fitting is used to estimate the damage probability of a tank in the case of earthquakes (Salzano et al., 2003); logistic regression is for example applied for fragility assessment of storage tank to flooding (Yang et al., 2020), etc. For domino effects, many tools, like event trees (Bernechea et al., 2013), Bayesian Networks (Khakzad et al., 2013), Petri-nets (Kamil et al., 2019), Monte Carlo simulation (Huang et al., 2020), and a matrix-based model (Zhou and Reniers, 2018), are used to estimate the failure probability of chemical installations. Recently, some methods, like Bayesian networks (Naderpour and Khakzad, 2018) and Monte Carlo simulation (Huang et al., 2020), are further applied for the probability estimation of Natech domino effects.

In the following step, risk assessment is usually performed by a professional QRA team to determine the risk level of the investigated chemical industrial area. Previous studies provide some available risk assessment methods considering Natech domino effects (Cozzani et al., 2014; Misuri et al., 2020a, 2021b; Huang et al., 2020; Krausmann et al., 2016), which is out of the scope of the present study. The QRA results need to be compared with the statutory risk acceptance criteria, and if the risk level is lower than the criteria, the early barrier system is established; otherwise, more safety barriers are needed.

The identification of key installations provides a preliminary importance ranking of chemical units, which guides the allocation of complementary safety barriers. Several complementary barrier sets can be obtained considering different combinations and allocations of safety barriers. However, only one barrier set can be applied to the chemical industrial area, how to select the optimal one is a complex decision problem. The most important constraint condition is ensuring that the risk level becomes lower than the risk acceptance criteria through the use of safety barriers. Other constraints can also be adopted in the decision problem, such as the minimum cost, the shortest installation time, the maximum safety benefits under a limited budget, etc. The optimal complementary barrier set can then be found using some decision algorithms, in which techniques such as analytic hierarchy process (AHP) or Monte Carlo Analysis (MCA) are employed. Then, the early barrier system can be established, including the basic safety barriers and the complementary barriers.

4.2.2. Operation stage

In this stage, the main work aims to establish an advanced barrier system to strengthen the resisting and response ability, hence the resilience, of the chemical industrial area. Compared to the design & construction stage, the operation stage is a long-time period, some new problems emerge. On the one hand, although technical safety barriers within the early barrier system are fully functional after installation and testing, the barrier performance may degrade with time. On the other hand, as Reniers et al. (2018) pointed out, tackling Natech domino effects needs multi-discipline knowledge. Safety knowledges would develop due to the communication and consultation of expertize and experience of different disciplines, resulting in a deeper understanding for risk factors.

A M&E box is established to maintain the performance of technical safety barriers (M module) and to enhance procedural barriers based on the safety knowledge (E module). For the M module, a monitoring system is needed to diagnose the barrier status, which is comprised by two parts: data acquisition and information processing. Data acquisition aims to collect critical data using sensors, and information processing would verify the proper barrier state based on those gathered data. Regular maintenance activities are beneficial for keeping the performance of technical barriers. Once the barrier state is degraded, the corrective repair activities would be carried out to guarantee high performance of safety barriers. Moreover, in case of multiple safety barriers degraded in a certain period, the safety barriers around the key units should be prioritized for repaired so as to make the overall risk returning to the target quickly. After the maintenance or repair activities, the barrier status should be re-monitored by the monitoring system. In addition, the procedural barriers could be strengthened through the E module. The effectiveness of procedural barriers is relied on the safety knowledges of the operators, safety managers, firefighters, etc. Those players need be trained and taught through some specific programs or activities about Natech events, so that they could positively respond to the complex scenarios of Natech domino accidents.

Since the circumstance of the chemical industrial area and the safety cognition are dynamic, the barrier system could be continuously advanced through the M&E box, until the occurrence of an accident.

4.2.3. Accident stage

Some studies demonstrate that the protection and mitigation effects of safety barriers can be less-than-desirable since safety barriers may be damaged and/or their performances may be depleted in case of Natech events or domino effects (Krausmann et al., 2016; Khakzad et al., 2017; Misuri and Cozzani, 2021; Misuri et al., 2020b). For instance, Misuri et al. (2020b) quantified the failure probability of safety barriers in case of earthquake and flood. Khakzad et al. (2017) analyzed the ineffectiveness of sprinkler systems in the case that the connecting water tank is damaged due to domino effects. Therefore, the response process of the barrier system and the failures in an accident stage should be recorded. The information is useful to identify improvement parts of the barrier system.

4.2.4. Recovery and improvement stage

In this stage, the objective is recovering the damaged chemical industrial area and improving the barrier system. After the accident stage, it is evident that the system performance of chemical industrial area drops to the lowest value due to the damage of installations and equipment. The system performance needs to be recovered through some actions, such as repairing, replacement, or rebuilding. The time to full recovery (TTR) is a key indicator to assess restorative capacity (Chen et al., 2021a). The level of full recovery depends on the needs of managers. After the recovery activities, the system would reach a new stable state.

Besides, the occurrence of the accident indicates that the barrier system failed to prevent undesired events as expected. Three possible reasons causing the situation are possible: i) a number of safety barriers have failed or have been damaged during an accident, resulting in no or partially protection; ii) some risk factors have been neglected or unrecognized before the accident, resulting in undesirable protection effects of the barrier system; iii) due to a limitation of the budget, the barrier system is not able to protect all accident-related units. However, the response of the barrier system could mitigate the consequences of the accident, resulting in lower loss of system performance. The lower loss of system performance could short the TTR, leading to a more resilient chemical industrial area. Moreover, some procedural barriers, such as the availability of drawings and clear-up works, are beneficial for improving the level of preparedness to quickly recover from accidents.

The new stable system allows the enhancement of system resilience by learning from the experience (Cincotta et al., 2019). The accident process and the recorded files about safety barriers are analyzed by safety experts to identify the improvement parts of the barrier system and lessons learned for similar accidents. Three concepts can be employed to improve the barrier system based on accident lessons, which are: substitution, enhancement, and adding more safety barriers. The substitution concept is substituting safety barriers which easily fail during an accident by other more robust and more reliable safety barriers. The enhancement concept aims to improve the capacity of a safety barrier to keep its function during accidents. For example, coating waterproof materials on electronic components of safety barriers could guarantee that the barrier remains operational in case of flooding.

Obviously, the new barrier system is more effective for similar accidents.

4.3. Case study

The developed framework is applied to an illustrative tank farm that refers to the work of Men et al. (2022). The layout of the tank farm is shown in Fig. 7, and the features of storage tanks are listed in Table 4. For illustrative purposes, only pool fire is assumed as the likely accidental scenario in the case study. Men et al. (2022) also provided the estimated heat radiation intensity received by the different tanks, as shown in Table 5.

The tank farm is assumed to be exposed to the risk of flood-triggered Natech domino effects. A flood with the velocity of 0.5 m/s, the height of 2 m, and the return period of 500 years, is assumed as the reference scenario as in the article from Misuri et al. (2021a). Except for the hypothetical flood Natech domino effects scenario in the case study, the developed framework also allows addressing the Natech domino effects triggered by other natural hazards (e.g., lightning, earthquake, etc.).

Since the aim of the case study is not to perform a complete QRA and to discuss the detailed plan for allocating specific safety barriers, but rather to show the implementation of the developed framework. The acceptance criteria of accident frequency are adopted as a simplified alternative form of the risk acceptance criteria. Five conceptual safety barriers are available to prevent and mitigate flood-triggered Natech domino effects, which are described in Table 6.

In the design & construction stage, the acceptable accident frequency for a tank is set to 1×10^{-6} events/year. Moreover, the safety managers expect to control the fire accident as far as possible without using barrier 5. The Natech accident frequencies, overall accident frequencies and time to failure (*ttf*) for the different tanks are assessed by adopting available models in the literature (see Appendix A), and the results are reported in Table 7.

As shown in Table 7, the overall accident frequencies of all tanks exceed the acceptable value of accident frequency. Adding more safety barriers to reduce the accident frequency is necessary. In addition, according to the results of Natech accident frequency, the multi-source primary accident scenario is not considered since its occurrence frequency is too low. Clearly enough, even though only considering a two-source primary accident scenario, its occurrence frequency is 10^{-10} in order of magnitude.

In order to satisfy the requirements of safety managers, a barrier system can be established, including:

i) barrier 1 that is equipped on all tanks (T1–T6);
ii) barrier 2 that is equipped on five tanks (T1/T3/T4/T5/T6);
iii) barrier 3 that is equipped on three tanks (T4/T5/T6);

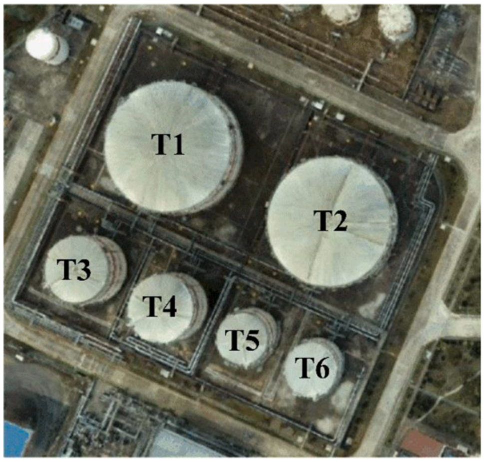

Fig. 7. Layout of the tank farm. (Referring to Men et al. (2022)).

Table 4
Features of storage tanks in the tank farm (Men et al., 2022).

Tank ID	Type	Stored substance (Density, kg/m^3)	Volume (m^3)	Height (m)	Diameter (m)
T1	Atmospheric	Gasoline (720)	20,000	17.8	40.7
T2	Atmospheric	Diesel (850)	20,000	17.8	40.7
T3	Atmospheric	Gasoline (720)	5000	18.8	21.1
T4	Atmospheric	Gasoline (720)	5000	18.8	21.1
T5	Atmospheric	Gasoline (720)	3000	17.3	17.1
T6	Atmospheric	Gasoline (720)	3000	17.3	17.1

Table 5
Heat radiation (kW/m^2) received by the different tank (Ti fire) (Men et al., 2022).

Ti→/Tj↓	T1	T2	T3	T4	T5	T6
T1	/	12.19	13.76	11.20	8.72	5.03
T2	10.83	/	5.16	9.11	12.67	13.55
T3	12.23	5.16	/	27.92	9.11	5.04
T4	11.20	10.47	31.43	/	31.43	11.54
T5	8.72	14.26	10.47	31.43	/	31.43
T6	5.03	15.25	5.90	11.54	31.43	/

Table 6
Available conceptual safety barriers in the case study.

Safety barrier	Description	Assumed performance (successful activation)
Barrier 1	The barrier may be comprised of single or several passive barriers, aiming to enhance the flood-resisting ability of tank.	The failure probability of a tank exposed to the flood would be reduced to 1/10 of origin value.
Barrier 2	The barrier may consist of some active and/or passive barriers to limit the ignition sources in the case of Natech event.	The ignition probability would be reduced to 1/10 of origin value.
Barrier 3	The barrier usually belongs to active barrier, which could mitigate the intensity of heat radiation received by the target unit.	The heat radiation would be reduced to 60% of origin value.
Barrier 4	The barrier is a fast but limited procedural barrier, which allows only extinguishing one fire.	The firefighters and firefighting resources would be available in 6.5 min.
Barrier 5	The barrier is a strong procedural barrier to control all fires, but it needs more time and more resources.	The firefighters and firefighting resources would be available in 20 min.

iv) barrier 4 and barrier 5.

Then, the accident frequency and *ttf* of each tank are re-assessed (see Table 8), and the results satisfied relevant requirements.

Subsequently, the tank farm enters the operation stage. M module in the M&E box is operated to maintain the performance of barrier 1, barrier 2 and barrier 3. E module could enhance the efficiency of barrier 4 and barrier 5, the arrival time of firefighters and firefighting resources decrease to 6 min and 16 min, respectively.

The tank farm enters the Section 4.2.3 when an accident occurs. Some assumptions for the accident are given, that are: i) at time t_f, T1 and T3 are damaged by the flood, and barrier 3 that equipped on T4 is failed due to water intrusion; ii) T1 and T3 catch fire at time t_p (remarking as 0 min); iii) target unit would be on fire when the heating

Table 7
Accident frequency and *ttf* for the different tanks.

Tank ID	T1	T2	T3	T4	T5	T6
Natech accident frequency	2.46×10^{-5}	3.16×10^{-6}	1.94×10^{-5}	1.94×10^{-5}	2.04×10^{-5}	2.04×10^{-5}
Overall accident frequency	2.49×10^{-5}	3.47×10^{-6}	3.50×10^{-5}	5.38×10^{-5}	5.39×10^{-5}	3.86×10^{-5}
ttf	/	/	6.61 min	5.79 min	6.10 min	6.10 min

ttf is estimated in the case of the maximum heat radiation received by the target tank from a single fire. For target tank T1 or T2, no single fire accident could lead to its escalation since the received heat radiation is below the threshold (15 kW/m^2).

Table 8
Accident frequency and *ttf* for the different tanks considering the barrier system.

Tank ID	T1	T2	T3	T4	T5	T6
Overall accident frequency	5.56×10^{-7}	6.26×10^{-7}	8.96×10^{-7}	9.91×10^{-7}	9.61×10^{-7}	7.40×10^{-7}
ttf	/	/	6.61 min	10.30 min	10.87 min	10.87 min

time (received heat radiation exceeds the threshold) is higher than the *ttf*; iv) the tank cannot get fire again if its fire has been extinguished; and v) barrier 3 is activated when the heat radiation received by the protected tank exceeds the threshold. The evolution process of accidents considering the intervention of the barrier system is depicted in Fig. 8. As shown in Fig. 8, barrier 4 performed at t_2 to extinguish the fire on T4 is the optimal strategy, avoiding the fire propagation to T5. If T4 and T5 catch fire simultaneously, the emitted heat radiation is very high, which may lead to a quick fire spread in the tank farm.

In the recovery & improvement stage, except for the recovery works, the barrier system could be improved based on the accident lessons. Firstly, adding more flood-resisting safety barriers is needed to protect tanks. Secondly, more effective and advanced barrier for ignition suppression should be introduced to substitute the origin one, further reducing the ignition probability. Thirdly, barrier 3 needs to be enhanced to ensure its operation in flood environment. Besides, improving the efficiency of procedural barriers still is important in the next operation stage. Take the Natech domino accident in Fig. 8 as an example, if the response time of barrier 4 is less than 4.1 min, the consequence can be limited to primary accidents.

4.4. *Discussion*

The framework presented in Fig. 6 provides a holistic and self-improving barrier management scheme against Natech domino effects, supporting safety strategies in the process industry. The developed framework points the attention of stakeholders to the whole cycle of a chemical industrial area, explicitly addressing the allocation optimization of safety barriers considering the characteristics of Natech domino effects. There are some challenges with respect to methods and tools for the implementation of the developed framework.

The first challenge is the complex scenario analysis of Natech domino effects. Since Natech domino effects being a new emerging topic in process safety, existing methods were developed based on some assumptions and simplifications, such as only focusing on the direct damage of chemical units due to a natural event and assuming the

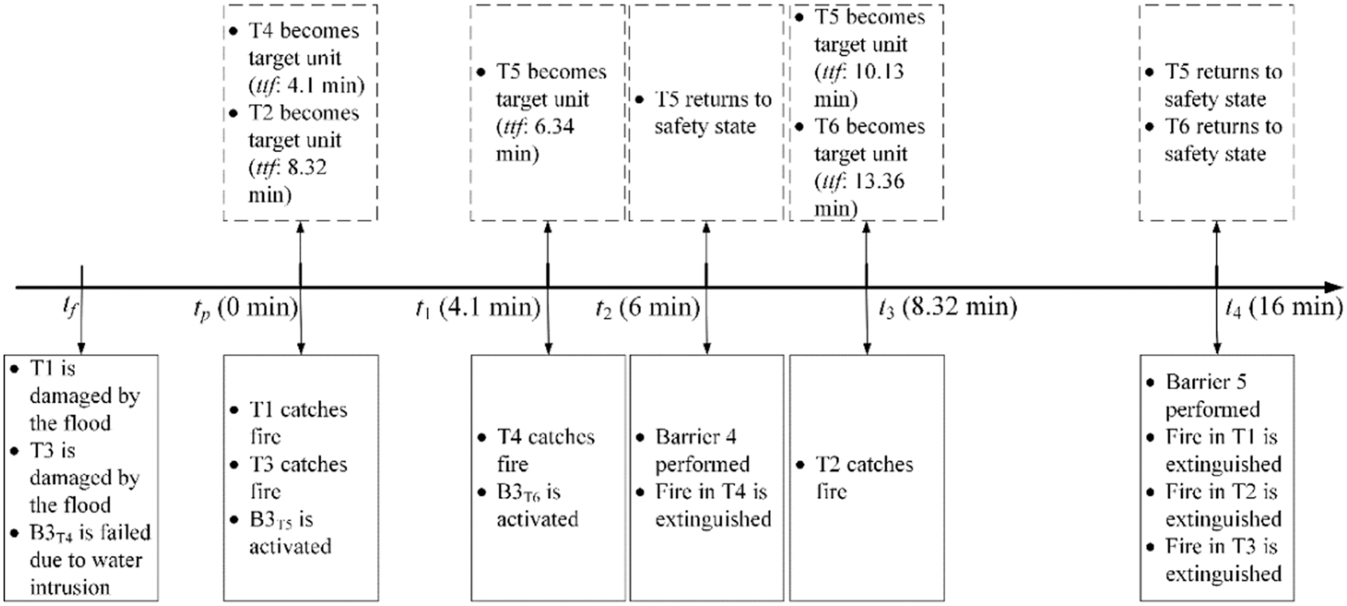

Fig. 8. Evolution process of accident. (B3$_{T4}$, B3$_{T5}$, B3$_{T6}$ are the barrier 3 that are equipped on T4, T5, T6, respectively).

strength of the natural event is a constant value in the investigated area. Those assumptions may lead to an inaccurate estimation of Natech domino effects risk. For example, in the case of floods, the leaked chemical may disperse or react with the floodwater (Cozzani et al., 2010), and the flood-loading may change between two rows of chemical installations due to flow interference (Zeng et al., 2021). Some ad-hoc models for those specific scenarios are needed to achieve a better analysis of Natech domino effects.

Another specific challenge is the integration of barrier analysis and QRA. Many studies contribute to the performance assessment of safety barriers and address the QRA of domino effects accounting for the effects of safety barriers (Landucci et al., 2017; Misuri et al., 2020b, 2021a, 2021b). However, there are still some gaps for the implementation of QRA considering the effects of safety barriers on Natech domino effects. On the one hand, previous studies mainly investigate the protective effects of safety barriers from the viewpoint of probability, but the intervention of barriers in accident consequences, more specifically coupled consequences due to simultaneous accidents, are seldom considered (Yuan et al., 2022). On the other hand, the performance degradation of safety barriers due to natural hazards deserves more attention since such phenomenon might lead to a significant increase in the probability of unmitigated cascading scenarios (Misuri et al., 2021a). Procedural barriers are more sensitive due to the physical impediment of natural events and the panic of personnel. Therefore, new techniques and methods should be developed to address those problems, providing a more robust QRA.

A further challenge is the data utilization for intelligent inspection. With the development of intelligent technology, a data-driven approach is adopted in the process industry to deal with some complex tasks such as monitoring, detecting, diagnosis and decision (Arena et al., 2022; Yuan et al., 2022), which is an advantage for the analysis of performance degradation of safety barriers and repair works. However, the fault of sensors, poor understanding of available data, and over-analysis of data might result in a false diagnosis of the barrier status. Research on optimization algorithms to process massive collected data and the reveal of the near-real-time barrier status is still needed, possibly effectively improving the intelligent level of barrier management.

5. Conclusions

In this paper, various concepts of ‘safety barrier’ and the principles of barrier management are reviewed to reveal the essential characteristics of safety barriers and the key factors of barrier management. Subsequently, the systemic and cascading nature of Natech domino effects is recognized and discussed. The accident sequences and causal relationships of different Natech domino effects are further analyzed. The prevention and mitigation schemes using safety barriers are explored in form of a bow-tie diagram, and four safety functions of safety barriers are outlined. Then, a holistic framework for barrier management against Natech domino effects is developed, covering the whole cycle (design & construction stage, operation stage, accident stage, and recovery & improvement stage) of a chemical industrial area. The developed framework aims to establish a barrier system in the design & construction stage and to improve it in the other three stages. Finally, challenges for the successful implementation of the framework are discussed, including complex scenario analysis of Natech domino effects, integration of barrier analysis and QRA, and data utilization for intelligent inspection, in the perspective of more adequate and intelligent barrier management.

Declaration of Competing Interest

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

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Appendix A

This appendix shows the calculation method for overall accident frequency and relevant parameters given the reference scenario of flood Natech domino effects in the case study.

The overall accident frequency of a single unit can be calculated according to the following equation (Abdolhamidzadeh et al., 2010; Zeng et al., 2021):

$$f_{\text{total}} = f(convention) + f(Natech) + f(domino) \tag{A1}$$

where *f*(*convention*) is the conventional accident frequency, referred to as 3.1×10^{-7} events/year (including ignition probability) (Antonioni et al., 2007); and *f*(*Natech*) and *f*(*domino*) are the accident frequency due to floods and accidental escalation, respectively.

Since only pool fire is considered in the case study, if the expected frequency of a reference flood is known, *f*(*Natech*) may be calculated as follows:

$$f(Natech) = f_{flood} \times P_{damage} \times P_{ignition} \tag{A2}$$

where f_{flood} is the expected frequency of the reference flood, which can be estimated from the return period; P_{damage} is the damage probability of a chemical unit exposed to a flood, which can be assessed by the vulnerability model (the adopted vulnerability model (Landucci et al., 2012) is reported in Table A1); and $P_{ignition}$ is the ignition probability when the chemical unit is damaged ($P_{\text{ignition}} = 0.01$ for diesel, and $P_{\text{ignition}} = 0.065$ for gasoline according to Men et al., 2022).

Table A1
Vulnerability model for chemical tank exposed to floods (Landucci et al., 2012), with values of relevant parameter for the application to case study.

Vulnerability model	Description of parameter	Value
$P_{damage} = \frac{CFL - \phi_{\min}}{\phi_{\max} - \phi_{\min}}$	CFL: Critical filling level	/
$CFL = \frac{0.5k_w\rho_w {v_w}^2 + \rho_w h_w g - P_{cr}}{\rho_f Hg}$	P_{cr}: Tank critical pressure	/
$P_{cr} = -0.199V + 6950$	$\Phi_{\min}$: Minimum operative filling level	0.01
	$\Phi_{\max}$: Maximum operative filling level	0.75
	k_w: Hydrodynamic coefficient	1.8
	ρ_w: Density of floodwater	1100 kg/m^3
	v_w: Flood velocity	0.5 m/s
	h_w: Flood height	2 m
	g: Gravitational acceleration	9.81 m/s^2
	ρ_f: Density of stored substance	Reported in Table 4
	H: Tank height	Reported in Table 4
	V: Tank volume	Reported in Table 4

For the estimation of $f(domino)$, the probability model developed by Abdolhamidzadeh et al. (2010) is adopted. Considering a chemical industrial area with n chemical units (u_1, u_2, …, u_n), for unit u_i, accident frequency due to domino effects can be expressed as:

$$f(domino) = P(E_{1,i} \cup E_{2,i} \cup \cdots \cup E_{i-1,i} \cup E_{i+1,i} \cup \cdots \cup E_{n,i}) \tag{A3}$$

where $E_{1,i}$, $E_{2,i}$, $E_{i\text{-}1,i}$, $E_{i+1,i}$, $E_{n,i}$ are the accident escalation on u_i (i.e., u_i catches fire) triggered by fire on u_1, fire on u_2, fire on $u_{i\text{-}1}$, fire on u_{i+1}, fire on u_n, respectively. In particular, if the fire probability of u_j (j ‡ i) equals 0 or the heat radiation received by u_i is lower than the threshold (15 kW/m^2 for atmospheric vessel), event $E_{j,i}$ can be not considered.

The probability of event $E_{j,i}$ can be expressed as (Abdolhamidzadeh et al., 2010):

$$P(E_{j,i}) = P_{j,fire} \times P_{escalation} \tag{A4}$$

where $P_{j,fire}$ is the probability of u_j being on fire, and $P_{escalation}$ is the probability of escalation given u_j being on fire.

$P_{escalation}$ can be obtained using the profit model (Landucci et al., 2015; Reniers and Cozzani, 2013):

$$P_{escalation} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} e^{-u^2/2} du \tag{A5}$$

where Y is probit value.

For fire-related domino effects, Y can be calculated by Eq. (A6) (Landucci et al., 2015):

$$Y = 9.261 - 1.85 \ln(ttf) \tag{A6}$$

where ttf is the time to failure of target unit, min.

For atmospheric vessel, ttf can be estimated by the following formula (Landucci et al., 2015):

$$ttf = 0.0167 \times \exp(-2.667 \times 10^{-5} V - 1.13 \ln(Q) + 9.877) \tag{A7}$$

where V is the vessel volume, m^3; Q is the received heat radiation, kW/m^2.

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