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A state-of-the-art review on their classification, assessment, and management

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Safety barriers in the chemical process industries: A state-of-the-art review on their classification, assessment, and management

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A R T I C L E I N F O

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A B S T R A C T

Barriers are used in various forms to assure the safety of chemical plants. A deep understanding of the literature related to safety barriers is essential to tackle the challenges in improving their design and management. This paper first provides an overview of the history of the development of the safety barrier concept. Subsequently, this paper elaborates a systematic review of the definition, classification, evaluation, performance assessment, and management of safety barriers in the chemical process industries. Based on the literature review, this study proposes a practical classification of safety barriers benefiting the identification of performance indicators and the collection of indicator-related data for safety barriers. The safety barrier functions are extended and illustrated by involving the resilience concept. Performance assessment criteria are proposed corresponding to the adaptability and recoverability of the safety barriers. Finally, the management of safety barriers is discussed. The roadmap for future studies to develop integrated management of safety and security barriers to ensure the resilience of chemical plants is suggested.

1. Introduction

As a commonly used term to present preventive measures, safeguards, mitigation measures, and protective layers to prevent or mitigate accidents, "safety function" or "safety barrier" is generally used. The latter concept originated from the energy model (Gibson, 1961). The term "safety barrier" firstly appeared in 1973 (Haddon, 1973). Then Johnson (1975) involved the safety barrier concept into the MORT (Management Oversight and Risk Tree) technique, in which the barrier analysis was emphasized and investigated. Although the safety barrier concept appeared already at the beginning of the 1970s and has been continuously further developed, a universally accepted definition of safety barrier has never been achieved. Different terms similar to "safety barrier" were used in various industries organizations. As an example, the term "protection layer" was used in the process industry as a similar function of "safety barrier" at an early age (CCPS, 1993). Svenson developed an accident evolution and barrier function (AEB) model that can be used to conduct accident evolution analysis to give suggestions for increasing safety in the process industries (Svenson, 1991). Then, the concept and functions of the so-called "safety barrier" were elaborated by Hollnagel in 1999 (Hollnagel, 1999a, 1999b) before some researchers tried to interpret and define safety barriers clearly to reduce misconceptions in work related to risk management and accident prevention (Duijm et al., 2004). Additionally, the ARAMIS (Accidental Risk Assessment Methodology for Industries) project developed an integrated approach for modelling and managing risks related to major hazard plants in Europe since 2001. The concept of safety barrier was applied and highly recommended. (Andersen et al., 2004; Duijm et al., 2004; De Dianous & Fievez, 2006). Khan et al. (2001) proposed a Safety weighted hazard index (SWeHI) tool for hazard identification and safety evaluation of chemical process industries with the consideration of technical and non-technical safety measures. Furthermore, a systematic study was conducted to present how safety barriers and similar concepts were interpreted and used in various industries. The classification of safety barriers and the performance of safety barriers were thoroughly investigated in this study (Sklet, 2006). The Petroleum Safety Authority Norway (PSA) presented the principles for barrier management in the petroleum industry. It highlighted a need to make the regulatory requirements related to barrier management more easily accessible (PSA, 2013). Meanwhile, the concept of safety barrier was also mentioned and

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stressed in other European regulations, national-level regulations, and international standards since the 1990s (Ec, 1996, 1998; Iec:61508, 1998; Iso:13702, 1999; Iso:17776, 2000; Iec:61511, 2002). The literature above indicates that the concept of safety barrier was widely used in different industries and played an essential role in hazards control and risk management-related policies and strategies. Furthermore, ISO standards (Iso:13702, 1999; Iso:17776, 2000; Iso:13702, 2015; Iso:16530, 2017) provided the requirement of safety barriers to prevent and mitigate accidents in the petroleum and natural gas industries, and they elaborated on the importance of employing safety barriers to reduce the probability of accidents and reduce the consequences caused by the accidents.

With the emergence and popularization of the safety barrier concept in various areas, the evaluation of safety barrier performance became a crucial issue, which was also vital in the following risk analysis research. Typically, the safety barrier performance was considered to constitute three components: functionality/efficiency, availability/reliability, and robustness (Sklet, 2006). A set of properties including effective, independent, and auditable is also proposed as the requirements for safety barriers from a barrier management perspective (CCPS/EI, 2018). The terms “reliability/availability” and “effectiveness” can be used to describe the safety barrier performance in providing protection, being widely accepted and applied in some risk analysis works as well (Landucci et al., 2015; Landucci et al., 2016). A Dynamic Procedure for Atypical Scenarios Identification (DyPASI) method was applied to identify critical safety barriers in biogas production and upgrading facilities (Moreno et al., 2018b). As the research about the functions and performance of the safety barriers became more in-depth, many studies were conducted to improve the targeted system’s safety or integrity status and assess the risks of the undesired accidents by modelling safety barriers or involving safety barriers into the risk assessment. An approach was proposed to improve the safety status of an interactive system by using the safety barriers modelling method (Basnyat et al., 2007). Landucci et al. proposed a method to assess the risks and frequencies of cascading events by presenting the availability and effectiveness of safety barriers in an event tree (Landucci et al. 2015, Misuri et al., 2021; Landucci et al., 2015; Bucelli et al., 2018; Misuri et al., 2021a). Additionally, the Bayesian Networks were also utilized in combination with safety barriers for dynamic assessment of the escalation scenario in offshore Oil&Gas (Bubbico et al., 2020) and fire-caused domino effects with good effectiveness (Khakzad et al., 2017a; Zeng et al., 2020). Recently, a review study was conducted by Liu to investigate the literature in the domain of safety barriers after 2006 (Liu, 2020). The studies on safety barriers were categorized into barrier theory, barrier engineering, and barrier management. In terms of safety barrier management, the graph theory (Khakzad et al., 2017b) and Bayesian networks (Khakzad et al., 2018) were combined with cost-effectiveness analysis to support decision-making on the allocation of safety barriers concerning fire-induced domino effects. A joint optimization model of safety barriers was proposed for enhancing the business continuity of nuclear power plants in case of steam generator tube rupture accidents (Xing et al., 2020). Regarding bow-tie diagrams, a joint publication by CCPS (USA) and Energy Institute (UK) describes how to conduct barrier management and barrier degradation control management based on bow-tie diagrams (CCPS/EI, 2018). Pitblado et al. (2015) proposed the Barrier-based Systematic Cause Analysis Technique (BSCAT) based on bow tie for incident investigation. The causation and safety barrier protection for the Buncefield accident are investigated. A bow-tie-based barrier alarm approach was developed to monitor accident processes mainly caused by the mechanical integrity of static equipment in the chemical industry (Schmitz et al., 2020). Moreover, an agent-based model was proposed to assess complex domino events and support the optimal allocation of safety barriers in the chemical industry (Ovidi et al., 2021).

Fig. 1 presents the timeline of the development of the literature on safety barriers in the chemical process industries. The first period is named “the origin period” when the specific term “safety barrier” did not appear yet. Still, a similar concept such as the one of safety barrier already existed. In the second stage, some primary contents about safety barriers were investigated, and the concept of safety barriers was used in some studies. The research work in this period focused on the concept, definition, classification, function, and performance criteria of safety barriers. In the next stage, the performance assessment of safety barriers became the focal point. Recent years have seen more studies on the performance optimization and management of safety barriers considering cost-benefit analysis.

As a critical infrastructure system with various hazards, the process industry poses high risks of multiple accidents, such as hazardous gas leakage, fire, gas explosion, and so on, caused by accidental defects or intentional attacks. The utilization of safety barriers is of great significance to prevent and mitigate accidents during the whole life-cycle of the process industry. Based on the above brief literature review, we identified the main issues as follows:

- In previous studies, the safety barriers were defined and classified based on the general features and functions of the safety barriers (Liu, 2020; Sklet, 2006). However, different types of safety barriers can be evaluated by various performance indicators. To support the identification of performance indicators and the collection of indicator-related data, a novel classification of safety barriers is demanded to give adequate support for safety barrier inspection, evaluation, and management.

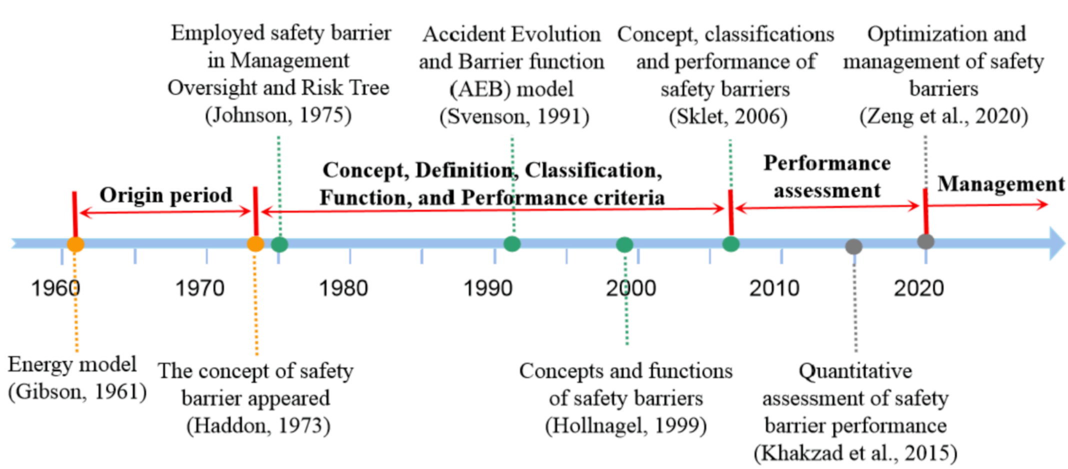

Fig. 1. History and highlight publications of safety barriers in the chemical process industry.

- The “effectiveness” and “availability”were widely used to describe the performance of safety barriers in previous researches (Landucci et al. 2015, Misuri et al., 2021; Landucci et al., 2015; Khakzad et al., 2017a). The adequacy of current performance evaluation criteria for safety barriers should be studied, particularly considering the involvement of the resilience concept (Reghezza-Zitt et al., 2015).

Therefore, a systematic review and analysis of the classifications, performance assessment, and management of safety barriers in the process industries must be conducted. The main objectives of this paper are as follows:

- To review the development history and current research status on safety barriers, particularly within the scope of the chemical process industries.
- To summarize the existing classifications of safety barriers and develop a novel classification for safety barriers, focusing on identifying and managing performance indicators.
- To identify safety barrier functions and propose corresponding performance evaluation criteria for safety barriers using the resilience concept.
- To identify the knowledge and technical gaps in current studies and provide suggestions on several aspects of safety barrier management for future works.

The terms have similar meanings to “safety barrier” such as “safety function”, “safety measure”, “safeguards”, “protective layer,” etc. were all considered as review terms in this study. Meanwhile, only the references relevant to the aims of this paper were selected and discussed. Thus to ensure a suitable scope of this review and to achieve our research objectives. The remainder of this paper is organized as follows. Firstly, the definitions of “safety barrier” from an early age are systematically reviewed in section 2. Then, the different classifications of safety barriers are analyzed, and a novel classification of safety barriers is proposed in section 3. The studies related to the assessment of safety barriers and the approaches used for safety barrier modelling are analyzed in section 4. The methods and strategies used for safety barrier management and the knowledge and technical gaps are illustrated in section 5. Finally, future research pathways and conclusions are presented in section 6 and section 7, respectively.

2. The definition of safety barrier

Although the concept of safety barrier originated decades ago and has been applied in practice for many years, a unified definition of a safety barrier has not been derived. Some terms, like protection layer, defence, safety measures, safety functions, safeguards, etc., were also used to present a similar meaning of safety barrier in different industries worldwide.

2.1. The conventional definition of safety barrier

In this paper, the classical definition of a safety barrier refers to viewing a safety barrier as a physical protection barrier (Holland, 1997). There are distinctions between different definitions regarding which extent barriers should influence the energy flow or event sequence. On the one hand, a barrier should “reduce the probability of an accident'' or “reduce the consequences of an accident'' (Iso:17776, 2000). On the other hand, a barrier should “prevent the flow'' (Holland, 1997) and should be capable of preventing a scenario from proceeding to the undesired consequences (CCPS, 2001).

In the classical definitions, a safety barrier is regarded as a physical obstacle, obstruction, or hindrance to protecting “a target” from “hazards” (Sklet, 2006). A safety barrier is related to a hazard, an energy source, or an event sequence. This indicates that safety barriers should be related to a specific hazard to specify their functions and locations. As a physical structure or obstacle, a safety barrier can be used to prevent or delay the occurrence of accidents and/or mitigate the severity of their consequences.

2.2. The extended concept of safety barrier

Apart from the conventional definition, the concept of safety barrier was extended to have a broader scope to include non-physical barriers. Defence-in-depth (DiD), known as a military strategy to delay rather than prevent the advance of an attack through design, process, and scenario-based approaches (Fleming & Silady, 2002), was applied to expand the definition of the safety barrier. DiD was regarded as the basis for the extended concept of safety barrier (Sklet, 2006). The definitions of DiD evolved from a relatively simple set of strategies to apply multiple lines of defence to a more comprehensive set of cornerstones, strategies, and tactics to protect public health and safety (Fleming & Silady, 2002). As a result, the term safety barrier is used in a broader meaning as a collective term for different means used to realize the concept of DiD. DiD adopts several levels of protection barriers, including the protections of targets from accidents and the protections of the barriers themselves. Some further measures were included in this concept to protect the public and the environment from hazards and damages, including the measures to preserve the effectiveness of the barriers. Accordingly, the modern principle of DiD combines different types of barriers, from physical obstacles, protection measures to strategies and safety policies. Similarly, some broader definitions of safety barriers were proposed by researchers, such as Schupp et al. defined safety barriers as the combination of technical, human, and organizational measures that prevent or protect against an adverse effect (Schupp et al., 2004). Johnson defined safety barriers as the diverse physical and organizational measures taken to prevent a target from being affected by a potential hazard (Johnson, 2003).

The concept of “protection layer”, which whereby a device, system, or human action is provided to reduce the likelihood and/or severity of a specific loss event, has a similar meaning as the concept of “safety barrier” (CCPS, 2001). If the protection layer can meet the requirements of independent, functional, integrity, reliable, validated, maintained and audited, access security, and management of change, it becomes a separate protection layer (IPL) (CCPS, 2021). Identifying IPLs and estimating the probability of failure on demand (PFD) of each IPL is an integral step during the implementation of LOPA (Layer of Protection Analysis). CCPS (USA) and Energy Institute (UK) defined a barrier based on the bow tie diagram as a risk reduction measure that on its own can prevent a threat from developing into a top event or can mitigate the consequences of a top event (CCPS/EI, 2018). In the same study, a barrier is considered a complete system fulfilling the criteria of being effective, independent, and auditable, similar to the characteristics defined in LOPA for an IPL (CCPS, 2001). According to this definition, a barrier can perform the complete intended function on its own when demanded. Meanwhile, active barriers are considered must-have separate elements of ‘detect-decide-act’, i.e., ‘detect’ a change in condition or what is going wrong, ‘decide’ what action is required to cope with the change and ‘act’ to stop the threat from progressing further.

By reviewing the extended concept of safety barrier, we define a safety barrier can be a physical or non-physical tool planned to prevent, control, or mitigate undesired events or accidents. The means of safety barriers can vary from a technical facility or human action to a complex socio-technical system. Undesired events and accidents can be technical failures, human errors, external events, or a combination of these occurrences that may cause potential hazards, leading to loss of human lives, personal injuries, environmental damage, and/or material damage. The purposes of the safety barrier are to reduce the risk of an undesired event, limit the extent and/or duration of an undesired event from escalation, and reduce the impacts of an undesired event or accident. Our proposed definition is different from the definition proposed by CCPS (USA) and Energy Institute (UK). The safety barrier should always be able to perform a complete safety function on its own. The active barriers should have the three elements of "detect – decide – act" (CCPS/EI, 2018). Under our definition, there are fewer requirements for a safety barrier, thus involving more technical and non-technical measures into the barrier concept, which is consistent with many previous definitions, such as the definitions concluded in review papers (Liu, 2020; Sklet, 2006). In this way, the barriers with just one of these elements (e.g., gas sensors or emergency shutdown valves) that don't meet the requirements of safety barriers in CCPS/EI (2018) can be regarded as safety barriers under our definition. A complete active safety barrier in the definition of CCPS/EI (2018) is preferred to be called a barrier system concerning our definition.

To clearly compare the conventional and extended concepts of safety barriers, we conclude the features of different definitions in Table 1. As shown in Table 1, only physical items are included in the conventional definition, while both physical and non-physical objects are included in the extended definition. The implementation methods of safety barriers in the traditional definition are narrower than the extended definition as only physical tools are involved in the conventional definition. Whereas, in the extended definition of a safety barrier, strategies, human action, socio-technical system, organizational measures, etc., can be applied to prevent, control, or mitigate undesired events or accidents in the whole life-cycle process industries. Additionally, one point is that the safety barrier in the conventional definition should always be related to a specific hazard and only be used for physical protection. In contrast, the extended concept of safety barrier can be applied to a large field, including improving inherent safety designs and reducing organizational errors.

3. Classifications of safety barriers

In this section, the previous classifications of safety barriers are summarized firstly. Then a new method is proposed to categorize safety barriers concerning the practicability and feasibility of using it in safety barrier management in the process industries.

3.1. Existing classifications

According to the previous studies, most of the classifications of safety barriers are based on the extended definition of safety barrier, which involves physical and non-physical objects. Typically, many researchers classified safety barriers into physical barriers and non-physical barriers, in which the non-physical barriers were classified further as well. Additionally, some studies classify safety barriers according to the operational features or functions of the safety barriers. Such as, passive barriers and active barriers were widely used to present barriers that are not required to be activated to achieve their function and the barriers that are necessary to move from one state to another in response to a change or a signal to fulfill their role respectively (Sklet, 2006). A classification scheme proposed by AIChE (CCPS, 2001) divides safety barriers into the inherently safer design barriers, passive barriers, active barriers, and procedural and emergency measures, which are also widely used in other researches (De Dianous & Fievez, 2006; Landucci et al., 2015; Landucci et al., 2016; Khakzad et al., 2017a).

Typically, some classifications of safety barriers were proposed based on the bow-tie model, which can illustrate the accident process by presenting hazards or potential causes of the central event on the left-hand side and the consequences of the central event on the right-hand side. Based on the bow-tie model, safety barriers used on the left-hand side of the bow-tie can be called "preventive" or "proactive" barriers, which are used to reduce the likelihood of occurrence of the central event. By contrast, the safety barriers used on the right-hand side of the bow-tie are called "reactive" barriers or "mitigating" barriers, which are used for mitigating the consequences of the central event (Liu, 2020). According to the joint publication of CCPS (USA) and Energy Institute (UK), barriers are suggested to be classified into five types based on the operating characteristic of the barrier. They are "passive hardware", "active hardware", "active hardware + human", "active human", and "continuous hardware" (CCPS/EI, 2018). Neto et al. (2014) employed the bow-tie model and LOPA to define the barriers and the relation among them, in which the barriers are comprised of nine layers of protection. Additionally, Van Nunen et al. (2019) and Swuste et al. (2019) categorized safety barriers into technical safety barriers, non-technical safety barriers, and management delivery systems based on the bow-tie model and assigned different types of indicators to the safety barriers to support occupational safety management. To facilitate the comparison and analysis, we summarize the typical classifications of safety barriers in Table 2.

As we can see from Table 2, the classifications based on "physical" or "non-physical" were widely proposed at an early age because such classification is intuitive. Meanwhile, considering other properties of safety barriers, they were also classified into "permanent" and "temporary" barriers (Hollnagel, 2004) and "static" and "dynamic" barriers (Holland, 1997). From another point of view, the classifications based on operational features were proposed with great practicality because it increases the effectiveness of the operation and management of safety barriers. Additionally, the classifications based on the bow-tie model are also of great feasibility and practicality, which can be combined with the bow-tie model to support the assessment and management of safety barriers.

3.2. Safety barriers in the process industries

Safety barrier management plays an essential role in terms of accident prevention and mitigation in the process industries. A reasonable and practicable classification of safety barriers is a crucial basis for assuring the process safety of a chemical plant or cluster. A practical research question that needs to be investigated is how to identify and determine proper safety performance indicators of safety barriers. Data can be collected based on these indicators, and analysis can be performed to support the inspection, evaluation, and management of safety

Table 1
Comparison of conventional and extended definitions of safety barriers.

Aspects of the definition	Conventional definition	Extended definition	
Dimensions	Physical protection	Physical protection	Non-physical protection
Means of implementation	Obstacle, obstruction, hindrance, fence, structure, etc.	Same as the classical definition	Strategies, human action, socio-technical system, organizational measures, etc.
Objectives	To prevent accidents from taking place, delay the occurrence of accidents, prevent or mitigate the impact of the accident consequences	To prevent, control, or mitigate undesired events or accidents, including reducing the risk of undesired events or accidents, limit the extent and/or duration of undesired events or accidents from escalation, and mitigate the impacts of undesired events or accidents	
Application domain	Should be related to a specific hazard, can be applied to the physical protection of fires, explosions, etc.	Can be applied to events or accidents caused by errors from technical facilities, human actions, inherent designs, organizations, external events, and a combination of those	

Table 2
Typical classifications of safety barriers.

Classifications	Classification basis	Examples	References
Physical and non-physical barriers	Physical or non-physical	Physical barrier: fireproofing material Non-physical barrier: emergency team	(Johnson, 1980), (PSA, 2002), et al.
Physical, technical, and administrative barriers	Physical or non-physical	Physical barrier: fireproofing material Technical barrier: water spray system Administrative barrier: safety training on employees	(Wahlstrom & Gunsell, 1998)
Physical, technical, human factors-organizational systems	Physical or non-physical	Physical barrier: fireproofing material Technical barrier: gas sensor monitoring Human factors-organizational system: emergency response team	(Svenson, 1991)
Physical, procedural or administrative, human action	Physical or non-physical	Physical barrier: fireproofing coating Procedural or administrative barrier: safety training on employees Human action: manual shut down	(Neogy et al., 1996)
Physical and management barriers	Physical or non-physical	Physical barrier: fireproofing material Management barrier: safety training on employees	(Doe, 1997)
Hardware and behavioral	Physical or non-physical	Hardware barrier: fireproofing coating Behavioral barrier: emergency evacuation	(Hale, 2003)
Hard and soft barriers	Physical or non-physical	Hard barrier: physical isolation wall Soft barrier: watching to ensure a process stays within acceptable parameter values	(Hudson & Hudson, 2015)
Permanent and temporary barriers	Natural attributes	Permanent barrier[1]: corrosion prevention system Temporary barrier[2]: foam-water sprinkler system	(Hollnagel, 2004)
Static and dynamic barriers	Natural attributes	Static barrier[3]: well packer Dynamic barrier[4]: stabbing valve	(Holland, 1997)
Prevention, protection, and mitigation barriers	Operational features	Prevention barrier: good engineering practice Protection barrier: safety instrumented systems Mitigation barrier: fire brigade	(Markowski & Kotynia, 2011).
Passive and active barriers	Operational features	Passive barrier: pressure safety valve Active barrier: foam-water sprinkler system	(Kjellén, 2000)
Passive barriers, active barriers, and procedural and emergency measures	Operational features	Passive barrier: pressure safety valve Active barrier: water spray system Procedural and emergency measures: emergency team	(CCPS, 2001), (Landucci et al., 2015), (Khakzad et al., 2017a), et al.
Passive, active, and procedural (or human action barriers)	Operational features	Passive barrier: fireproofing material Active barrier: water spray system Procedural (or human action barrier): regular manual inspection	(Goossens & Hourtolou, 2003)
Inherent design and add-on barriers	Operational features	Inherent design: land use planning Add-on barrier: pressure safety valve	(Schupp, 2004), (Kjellén, 2007)
Passive barriers, activated barriers, human actions, and symbolic barriers	Operational features	Passive barrier: retention bund Activated barrier: emergency blowdown system Human action: emergency team Symbolic barrier: passive warnings	(De Dianous & Fievez, 2006), (Guldenmund, et al., 2006)
Preventive barriers/proactive barriers and reactive barriers/mitigating barriers	Bow-tie model	Preventive/proactive barrier: detection of leaks Reactive/mitigating barrier: emergency evacuation	(Sklet, 2006), (Rausand, 2014)
Passive hardware, active hardware, active hardware + human, active human, and continuous hardware	Operational features and bow-tie model	Passive hardware: blast wall Active hardware: process control systems and safety instrumented systems Active hardware + human: operator-activated ESD valve Active human: operator detection and response Continuous hardware: ventilation system	(CCPS/EI, 2018)
Technical safety barriers, non-technical safety barriers, and management delivery systems	Operational features and bow-tie model	Technical safety barrier: emergency stop on a pallet mover Non-technical safety barrier: manual removal of leaking containers Management delivery system: training of pallet mover operators on removing leaking containers	(Van Nunen et al., 2019)

[1]Permanent barriers are usually part of the design base, for instance, as a response to an accident (Hollnagel, 2004).
[2]Temporary barriers are restrictions that apply for a limited period of time only, typically referring to a change in external conditions (Hollnagel, 2004).
[3]Static barriers are available over a “long” period of time. This situation applies during production/injection or when the well is temporary closed in (Holland, 1997).
[4]Dynamic barriers vary over time. This applies to drilling, workover, and completion operations (Holland, 1997).

barriers. However, the existing literature does not provide enough discussion on this point.

Based on the types of data, collection, and analysis methods, performance indicators of safety barriers can be divided into two categories: technical and non-technical (Van Nunen et al., 2019). The ways to collect the information of technical and non-technical indicators can be different, and the improvements that can be implemented to the technical and non-technical performance may vary as well, such as device updates which can improve the technical performance while organizational strategies can enhance some non-technical performance. Therefore, classifying indicators into technical and non-technical ones can better facilitate the data collection process. Proper tools and approaches can be developed for and applied to various categories of performance indicators. Landucci et al. (2020) categorized the performance indicators of safety barriers into technology, procedures (and organizational aspects), and people (observable behavior). Vierendeels et al. (2018) classified all aspects of safety science within an organization into the technological domain of observable factors, the organizational domain of safety climate perceptions, and the personal psychological domain of behavioral motivation. The safety climate perceptions and personal psychological domain are usually non-observable and cannot be measured directly. Therefore, with the consideration of the non-observable or intangible aspects, the non-technical indicators are further divided into observable and non-observable in this paper because some non-technical indicators are usually hard to be observed or measured, e.g., the indicators connected to the perception, awareness, cognitive, and psychology of people are impossible to observe or measure directly. The non-observable indicators can be defined as the indicators related to people's non-observable behaviors and cannot be observed or measured directly. A new classification of safety barriers was proposed in this paper concerning the relationship between safety barriers and safety indicators, as shown in Fig. 2.

Based on the safety performance indicators, safety barriers may be divided into technical, non-technical observable, and non-technical non-observable. As for technical safety barriers, human actions may not necessarily be involved in their activation and operation. Technical safety barriers can be assigned with only technical performance indicators, such as the accuracy, effectiveness ratio, response time, and other technical parameters of facilities. Technical safety barriers can be defined as the technical measures and facilities used to prevent and mitigate undesired events. By contrast, non-technical safety barriers can be defined as the safety measures and actions implemented (activated or operated) by humans or organizations. Thus, the performance of the non-technical safety barriers will be significantly influenced by human or organizational factors. Therefore, the non-technical safety barriers can be assigned with both technical and non-technical indicators. For example, the emergency response team can be regarded as a non-technical safety barrier with non-technical indicators such as the specialization of emergency responders. Furthermore, it brings difficulties in inspecting and evaluating some non-technical safety barriers because the non-observable indicators need to be assigned and evaluated. In that case, the non-technical safety barriers are classified into observable and non-observable further by considering if the non-observable indicators are required to be assigned, as shown in Fig. 2.

To have a clear view of the potential hazards, consequences, and safety barriers in an accident scenario, the bow-tie method was widely used to demonstrate and visualize the whole process of the accident scenario and present the safety barriers in a comprehensible way (Swuste et al., 2019; Van Nunen et al., 2019). This paper presents the proposed classification of safety barriers in a bow-tie model to demonstrate that this classification can be adapted to both scenario-specific barriers and management delivery systems, as shown in Fig. 3.

As shown in Fig. 3, the technical safety barriers (solid black rectangle), non-technical observable safety barriers (black striped rectangle), and non-technical non-observable safety barriers (white rectangle with black frame) used in the pre-active-event and post-active-event scenarios are scenario-specific safety barriers, which can be utilized to prevent a specific event and mitigate the consequences as well. By contrast, management delivery systems mainly play a role by enhancing/maintaining the performances of the scenario-specific safety barriers or increasing the accident response capabilities of the overall system. Therefore, the management delivery systems can be regarded as a series of safety barriers to prevent or mitigate the undesired events indirectly and be divided into technical, non-technical observable, and non-technical non-observable. The indicators assigned to the management delivery systems can be called general indicators, and the scenario-specific indicators can be linked to scenario-specific safety barriers (Van Nunen et al., 2019). Under this classification, the concept of degradation controls (safeguards) in CCPS/EI (2018), which act to mitigate the degradation and maintain the safety barriers, can be involved in the management delivery systems. The concept of management delivery systems is broader compared to "degradation controls" because the technical and non-technical measures used to enhance the various performances of scenario-specific safety barriers can also be concluded in management delivery systems. The terms "degradation control" or "safeguards" proposed by CCPS/EI (2018) mainly target barrier degradation, technical errors, or human errors aspect, the various measures used to improve the performance of barriers but not targeting the control of barrier degradation were somehow neglected. By contrast, the measures aiming to degrade control or maintain barriers can be involved in management delivery systems, but the measures used to enhance the performance or effectiveness of barriers can be considered part of the management delivery systems. Such as the upgrade of safety–critical facilities/systems and evacuation training can not be regarded as safeguards (degradation controls) according to the definition of CCPS/EI (2018) if they are not targeted with a specific degradation factor. However, they help to enhance the performance of barriers (technical systems or emergency evacuations) and can be regarded as an indirect safety barrier. Therefore, they can be regarded as a part of the management delivery systems. To illustrate the application of this classification, a list of different categories of safety barriers in the process

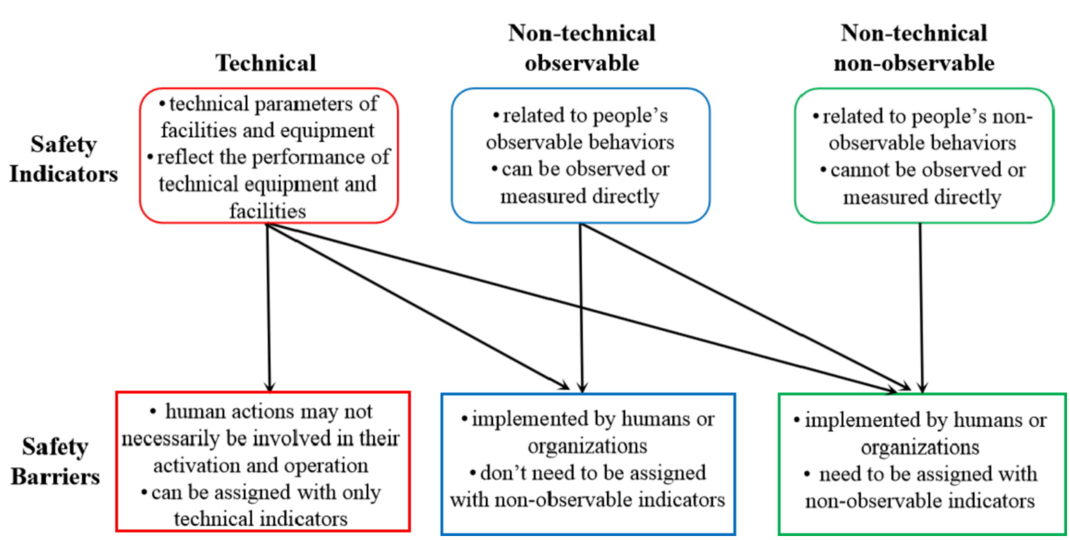

Fig. 2. Relationship between safety barriers and safety indicators.

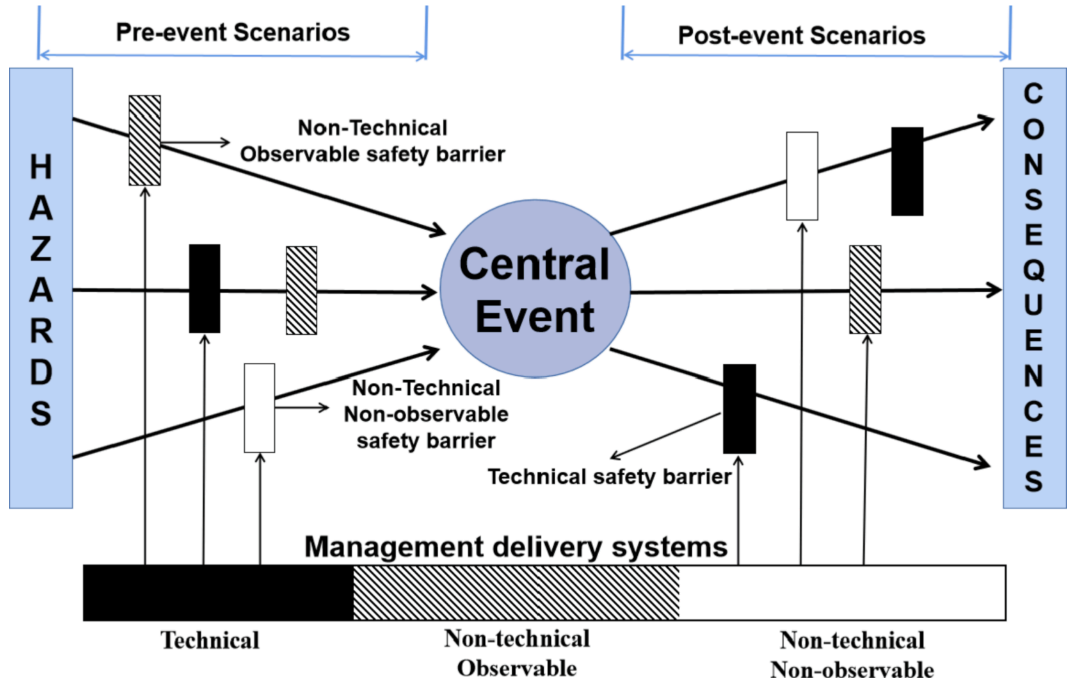

Fig. 3. Classification of safety barriers in the process industries.

industries concerning gas leakage accidents is provided in Table 3.

4. Performance assessment of safety barriers

Assessment of the safety barriers is critical to identify the risks and consequences of an accident scenario under the protection of safety barriers (Misuri et al., 2020). Moreover, evaluating safety barriers makes an indispensable part of risk and consequence assessment frameworks. It needs to be closely connected to the performance indicators, which may reflect the safety barrier functions. Therefore, it's inevitable to investigate the safety barrier functions and the corresponding evaluation criteria before reviewing the existing performance assessment methods and modelling methods of safety barriers used in the chemical and process industry.

4.1. Safety barrier functions

In previous studies, the safety barrier functions were closely connected to the classification of safety barriers. The realization of the barrier functions can be regarded as the core of a safety barrier system (Sklet, 2006; Liu, 2020). As a concept that originated from the energy-barrier-target model, it is common to see that the functions of safety barrier were described as preventing or mitigating undesired events or accidents and protecting the people, facilities, and environment from the corresponding damages (Hollnagel, 2004; Sklet, 2006). Therefore, the functions of safety barriers were always referred to with terms such as “avoid”, “prevent”, “control”, “mitigate”, “protect”, “limit”, “reduce” and so on (Andersen et al., 2004; De Dianous & Fievez, 2006).

As for scenario-specific safety barriers, they can be employed before the target event with the function of prevention and after the target event with mitigation on a goal. By contrast, inherent safety design prevents the target event or indirectly mitigates the consequences. However, it is inappropriate to identify the function of safety barriers only from a static accident-protection perspective. Apart from the prevention and protection perspectives, at least two factors can be considered to identify safety barrier functions. Firstly, the safety barrier can aim at a specific undesired event and enhance the comprehensive abilities of the overall industrial system, such as resistance ability, coping capacity, recovery ability, and so on. Therefore, it is necessary to identify the safety barrier functions from the perspective of the whole industrial system. Secondly, there are possibilities that the functions of a safety barrier (scenario-specific barrier or inherently safe design) can vary in different stages of an accident scenario and with the evolution of time. Therefore, the changes in the safety barrier functions in the whole event evolution cycle cannot be ignored. But unfortunately, the above two perspectives were overlooked in the previous studies.

The concept of resilience was adopted in this study to identify safety barrier functions from the above-mentioned two perspectives. The concept of resilience is to expand the traditional safety concept to have a proactive approach for safety barrier management (Jain et al., 2018; Ham, 2020). The necessity of expanding safety barrier management by involving the resilience concept was stressed by Liu (Liu, 2020). However, a detailed implementation method was not given in this study. Although the term resilience has many definitions according to different needs and practices (Reghezza-Zitt et al., 2015), the concept of resilience can provide broader content into the safety barrier theory and ensure safety barrier functions more comprehensively. According to the studies related to safety and resilience (Klein et al., 2003; Garcia-Dia et al., 2013; Proag, 2014; Lundberg & Johansson, 2015; Duchek, 2020; Proag 2014; Ham 2020) Bento et al., 2021), the concept of resilience derives from the socio-ecological systems. It can illustrate safety and accident topics from a new perspective (Bento et al., 2021). Based on various definitions, resilience is regarded as the ability of a system to adapt and absorb any internal and external negative impacts and maintain a normal state or achieve recovery to a normal state after disruptions. Typically, resilience can be classified into hard resilience and soft resilience (Proag, 2014), which can somehow correspond to technical safety barriers and non-technical safety barriers. The safety barriers can be involved in the whole resilience process, from the prediction before the undesired event to the recovery and learning after the undesired event. In previous studies, responding, monitoring, anticipating, and learning were regarded as the cornerstones of a proactive resilience system (Hollnagel, 2009; Patriarca et al., 2018). The components of organizational resilience were also identified as anticipation, coping, and adaptation from a process perspective (Duchek, 2020). In the same study, predicting potential risks and preventive actions before damage

Table 3
Examples of different categories of safety barriers in the process industries, particular according to gas leakage accidents.

Types	Examples	Scenario specific or not	Possible performance/safety indicators
Technical	Gas sensor monitoring	Yes	Technical indicators: monitoring accuracy, false alarm rate, response time, et al.
	Acoustic detection of leaks	Yes	Technical indicators: detect accuracy, detect cycle, et al.
	Emergency shut down system	Yes	Technical indicators: effective ratio, response time, et al.
	Emergency blowdown system	Yes	Technical indicators: ventilation rate, effective ratio, response time, et al.
	Technical system upgrade	No	Technical indicators: upgrade cycle, upgrade rate, et al.
Non-Technical observable	Manual blowdown	Yes	Technical indicators: ventilation rate of ventilators, et al. Non-Technical observable indicators: human response time, the number of responders, et al.
	Manual shut down	Yes	Technical indicators: effective ratio of shut down systems, et al. Non-Technical observable indicators: human response time, human error rate, et al.
	Emergency evacuation	Yes	Non-Technical observable indicators: the number of evacuation personnel, personnel speed, et al.
	Regular manual inspection	Yes	Non-Technical observable indicators: the number of inspectors, hazards detection rate, check cycle, et al.
Non-Technical non-observable	Evacuation training	No	Non-Technical observable indicators: training content, coverage ratio of training[5], et al. Non-Technical non-observable indicators: training quality, et al.
	Training of safety inspectors	No	Non-Technical observable indicators: training content, coverage ratio of training, et al. Non-Technical non-observable indicators: training quality, et al.

[5]Coverage ratio of training means the percentage of operators receiving a training. How to evaluate the coverage ratio of training can reference to (Van Nunen et al., 2019).

was considered as operations used in the anticipation stage. Additionally, terms such as detection and activation, response, and organizational learning were also used to present the resilience process (Burnard & Bhamra, 2011). Lundberg and Johansson have conducted a systematic resilience model study, in which the stages of a resilience process were classified into anticipation, monitoring, response, recovery, learning, and self-monitoring (Lundberg & Johansson, 2015). By investigating the above-mentioned studies and considering the technical and organizational characteristics of the process industry, the safety barrier functions were identified according to five resilience stages (anticipation, monitoring, response, recovery, learning) in this paper, as shown in Fig. 4.

The safety barriers can be employed in all the stages of a resilient process and play various functions. As illustrated in Fig. 4, safety barriers can be utilized to play different roles, such as identification, detection, prediction, and prevention at the anticipation stage, usually before the undesired event happens. In the monitoring stage, the technical monitoring, warning, and organizational monitoring functions can be used. The following stage concerns the response process, in which the functions of resist, mitigate, absorb, adapt and protect are mainly applied. In the recovery stage, the functions of the safety barrier can be divided into diagnosing, repairing, replacing, rebuilding, and recovering. Finally, safety barriers play functions as collect, learn and improve in the learning stage, usually after the undesired event. It should be noticed that the safety barrier functions used for self-monitoring being regarded as a separate stage were considered in this paper as safety barrier functions in the monitoring stage. The monitoring operations are generally conducted during the whole resilience process. We further explain all the safety barrier functions in Table 4.

4.2. Evaluation criteria of safety barriers

Developing reasonable evaluation criteria is the basis of safety barrier evaluation. Researchers already carried out this regard (Landucci et al., 2015; Kang et al., 2016; Moreno et al., 2018b; Misuri et al., 2020; Schmitz et al., 2020). The evaluation criteria should have the ability to reflect how well safety barriers perform their main capabilities for various accidental scenarios. A range of factors, including functionality, availability, reliability, independence, survivability, compatibility, maintainability, benefit, and cost were considered as performance standards for control measures and could be related to their effectiveness (NOPSEMA, 2020). Typically, effectiveness is widely regarded as an evaluation criterion to measure safety barrier performance. Kang et al. proposed a quantitative evaluation method for safety barriers considering three perspectives: confidence, effectiveness, and economic impact, in which the effectiveness was defined as how well a safety barrier can prevent accidents and reduce the risk to an expected level. (Kang et al., 2016). The terms such as efficiency and sufficiency were also used to describe the safety barrier with similar implications as the effectiveness (Liu, 2020).

Meanwhile, availability is also widely utilized to measure safety barriers from another perspective. The availability can be defined as the capacity of a barrier to performing its function effectively at a particular time, which is a time-dependent evaluation criterion (Liu, 2020). Generally, the availability can be combined with effectiveness to evaluate the safety barrier performance, especially for the active safety barriers. A series of studies have been investigated by Landucci et al. to evaluate and assess the safety barrier performance by using availability and effectiveness (Landucci et al., 2015; Landucci et al., 2016; Bucelli et al., 2018; Misuri et al., 2020). In those studies, the availability was presented and quantified by the probability of failure on demand (PFD) of the safety barriers. The effectiveness was described as the probability that the safety barrier will prevent the escalation after being activated successfully (Landucci et al., 2015). Additionally, the combination of effectiveness and availability was also used in the vulnerability assessment of chemical plants. The effectiveness was transformed to degradation protection measures over time (Khakzad et al., 2017b).

Additional evaluation criteria can be established by incorporating the concept of resilience into safety barrier management. Robustness and survivability with a similar meaning of adaption can describe the ability of a safety barrier to withstand extreme accidental interventions without losing its primary function (Liu, 2020). To evaluate the resilience of safety barriers, adaptability and recoverability have an excellent potential to measure safety barrier performance since being indispensable attributes of a resilient system. The concept of adaptive capacity originated from the context of climate change and was then used in the resilience domain (Klein et al., 2003). Although the adaptation was considered a separate stage of a resilience process in some studies (Duchek, 2020), we think it's more reasonable to regard adaptability as a kind of capacity existing in a resilient system and the safety barriers. In this way, the whole process of a resilient response can be adaptive, and the adaptability of a safety barrier can contribute to the adaptability of the entire system.

Therefore, we suggest extending the effectiveness and availability of a safety barrier by adding adaptability and recoverability from a time-

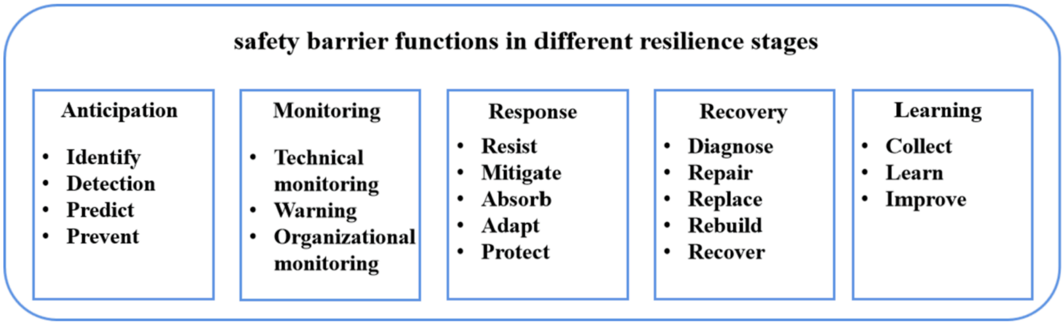

Fig. 4. Safety barrier functions in different resilience stages.

Table 4
Safety barrier functions in different stages of a resilient process.

Stages	Functions	Descriptions
Anticipation	Identify	Identify hazards existing in technical facilities and organizational management
	Detect	Detect defects and faults existing in technical facilities and organizations
	Predict	Predict causes, risks, consequences, and evolution scenarios of the undesired event
	Prevent	Take preventive measures before the undesired event happened, can be both technical and non-technical measures
Monitoring	Technical monitoring	Monitor status of facilities, humans, or the whole system by technical techniques
	Warning	Early warning when an abnormality occurs
	Organizational monitoring	Monitor status of organizations by non-technical techniques
Response	Resist	Resist the negative impacts caused by the undesired event
	Mitigate	Mitigate the negative impacts caused by the undesired event
	Adapt	Adapt the negative impacts caused by the undesired event
	Absorb	Absorb the negative impacts caused by the undesired event
	Protect	Protect humans, facilities, assets, and the environment from damage or negative impacts
Recovery	Diagnose	Diagnose faults and defects of the technical facilities and organizations
	Repair	Repair faults and defects of the technical facilities and organizations
	Replace	Replace damaged parts of the technical facilities and organizations or activate the backup scheme
	Rebuild	Rebuild the damaged functions of the technical facilities and organizations
	Recover	Recover the functions and status of the system
Learning	Collect	Collect and organize data and information of the whole process
	Learn	Find problems, learn new knowledge, and develop new techniques based on the collected data and information
	Improve	Improve the resilient system based on the learning results

dependent perspective. The adaptability of a safety barrier can be defined as the ability to withstand a varying environment, work conditions, and disturbances. The recoverability of a safety barrier can be defined as the ability to recover functions after disruptions. In this way, the changes in availability and effectiveness of a safety barrier, subject to operational conditions change and damage occurrence, can be further described using adaptability and recoverability. With the combination of evaluation criteria of availability, effectiveness, adaptability, and recoverability, safety barrier performance can be reflected from a resilience perspective. Meanwhile, safety barrier performance evaluation becomes comprehensive because the safety barrier functions can be evaluated under extreme environments, complex conditions, and accident scenarios.

4.3. Safety barrier performance assessment methodologies

This section discusses two categories of safety barrier performance assessment methodologies: static and dynamic performance assessment methods.

The event tree (Schüller et al., 1997) and LOPA (Basheer et al., 2019) were widely used in safety barrier assessment or IPL assessment because of their easy implementation. Xue et al. combined event tree analysis with the Swiss cheese model to assess the risk associated with safety barriers (Xue et al., 2013). A LOPA-based method combined with a modified event tree was proposed to conduct the static quantitative assessment of safety barrier performance in preventing the escalation of domino scenarios in the chemical industry, in which different types of gates were designed to consider the actual availability and effectiveness of safety barriers (Landucci et al., 2015; Landucci et al., 2016; Misuri et al., 2021a). This method was also modified to be applied in Natech scenarios (Misuri et al., 2020) and assessment of safety barrier performance with installations operating in harsh environments (Bucelli et al., 2018). A Bayesian–LOPA methodology was proposed to estimate potential risks of LNG terminals, in which the PFDs of IPLs can be estimated by using the Bayesian engine (Yun et al., 2009). The incorporation of human performance within LOPA was investigated, and the human performance within independent protection layers are reviewed before the methods for quantification of human performance were outlined (Myers, 2013). A LOPA-based approach called the cloud model layer of protection analysis (CM-LOPA) was proposed to assess gas leakage risk in a biomass gasification station (Yan et al., 2017). In the proposed approach, the expert judged risk was processed by the cloud model, and the quantified risk was presented as the cloud model risk (CMR). A simulation-oriented methodology for quantifying human error probability (HEP) in independent protection layers (IPLs) was proposed to conduct a comprehensive analysis of human actions during the operation of batch reactor systems (Zhu et al., 2020). The individual and societal risks of hydrogen refueling stations in urban areas was evaluated by employing LOPA with passive and active IPLs (Park et al., 2021). Additionally, the event tree analysis was employed for the risk assessments of offshore drilling systems and hydrogen refueling stations with quantitative probability analysis and qualitative consequences analysis. The failure probabilities of the safety barriers were considered (Ramzali et al., 2015; Tsunemi et al., 2019).

Apart from the event tree and LOPA, bow–tie diagrams were also widely used in the performance assessment of safety barriers. Such as the implementation of bow–tie diagrams in the evaluation of safety barrier performance was recommended in the ARAMIS project, and the specific implementation process was illustrated (Andersen et al., 2004; Duijm et al., 2004; De Dianous & Fievez, 2006). An approach based on the bow tie model was proposed to provide a more thorough treatment of human factors and organizational objectives in the barrier-based risk assessment (Pitblado & Nelson, 2013). Bucelli et al. (2017) integrated bow-tie based barrier management within the risk barometer methodology. In the same study, the status of barriers was evaluated considering the technical features and the whole series of operational and organizational activities aimed at establishing and maintaining them. A multi-objectives approach with the implementation of preventive and protective barriers based on bow tie diagram was proposed to conduct risk assessment of unconfined vapor cloud explosion (Badreddine et al., 2014). Sobral & Soares (2019) proposed a methodology to evaluate the adequacy of a safety barrier. The safety integrity level of an assessed safety barrier and the probability of occurrence of the hazardous event is linked. Ding et al. (2020) combined bow tie and Bayesian network models to investigate the relationships among accident causes, safety barriers, and the possible consequence of a cotton storage fire. Concerning the prevention of major accidents in the oil and gas sector, the quantification of safety barrier performance was investigated with the application of the ARAMIS project results. Meanwhile, the importance of the management factor in combination with technical and technological aspects of safety barrier performance was highlighted (Hosseinnia et al., 2021). Additionally, an incident process analysis was used to illustrate the evolution of an accident scenario concerning the failure of safety barriers (Kang et al., 2016). The failure frequency of safety-related systems was calculated by fault tree in association with protection layers (Innal et al., 2014), and a Petri net (PN) model was employed to modelling the evolution of faults in modern production systems by representing active safety barriers (De Souza et al., 2017).

Dynamic risk assessment (DRA) can be regarded as the basis for dynamic performance assessment of safety barriers. Dynamic risk assessment originated in the 2000s (Swaminathan & Smidts, 1999; Boudali & Dugan, 2005). Then, DRA methods have been widely developed and applied in the past few decades (Kanes et al., 2017). Typically, dynamic fault tree analysis (Rao et al., 2009), dynamic event trees (Hofer et al., 2004), bow-tie approach (Khakzad et al., 2012), dynamic Bayesian network (Khakzad, 2015), Monte Carlo simulation approach (Huang et al., 2021) and dynamic graph approach (Chen, 2019) were employed for dynamic risk analysis of accidents in chemical process industries. In terms of dynamic performance assessment of safety barriers, it brings enormous difficulties to the event tree method, LOPA, and bow-tie diagrams, which are more suitable for static assessment of barriers. By contrast, the dynamic Bayesian network, dynamic graph analysis, and Monte Carlo simulation approaches can achieve the dynamic performance assessment of safety barriers. The Bayesian Network (BN) was used in the quantitative evaluation of subsea blowout preventer operations in the offshore oil and gas industry (Cai et al., 2012; Cai et al., 2013) and risk assessment of cotton storage fire associated with safety barriers (Ding et al., 2020). Villa & Cozzani (2016) applied Bayesian Networks to quantitative assessment of the performance safety barriers in the context of major accidents prevention within the process industry. The BN-based methodology was developed to optimize Land-use planning (LUP) that can be regarded as an inherent safety measure in the risk management of chemical plants (Khakzad & Reniers, 2015; Khakzad & Reniers, 2017). And then, BN or DBN was used to achieve the dynamic performance assessment of safety barriers. Bubbico et al. (2020) combined Bayesian networks and safety barrier assessment to conduct a dynamic risk analysis of major accidents in Oil&Gas platforms. Dimaio et al. (2021) employed a multistate Bayesian network to model and evaluate the performance of safety barriers in Oil and Gas plants, in which the Key Performance Indicators (KPIs) related to the barrier characteristics were used to assess the health condition of safety barriers. The DBN-based methodologies were developed to assess the safety integrity levels (SILs) of the safety instrumented systems (Cai et al., 2016; Simon et al., 2019). Khakzad et al. combined DBN with event tree analysis to the dynamic assessment of add-on passive and active fire protection systems in case of escalation of fire domino effects (Khakzad et al., 2017a). Sun et al. (2021) proposed a performance assessment method for safety barriers. The DBN was employed to calculate the availability function with the consideration of the absorption, adaptation, and restoration capacities of the barrier systems. Additionally, dynamic graph analysis was utilized to assess the vulnerability of chemical plants concerning the escalation of cascading effects. The protection of safety barriers was considered (Khakzad et al., 2017b). Monte Carlo simulation was combined with a Markov-based approach for the dynamic performance analysis of subsea blind shear ram preventers (Wu et al., 2018). An agent-based model was proposed for risk assessment of complex domino events accounting for the influence of safety barriers. The transient evolution of multiple scenarios and the time-dependent degradation of barriers were considered (Ovidi et al., 2021). A list of publications related to safety barrier assessment is shown in Table 5, which also presents the characterization of those studies.

5. Safety barrier management

In this section, the research status of safety barrier management in the chemical process industry is presented, followed by an elaboration of the current knowledge and technical gaps of barrier management within the safety science domain.

5.1. Research status of safety barrier management

The management of safety barriers was widely investigated in previous studies from both the operation/maintenance perspective and design/allocation perspective. Barrier management was regarded as an integral part of the health, safety, and environmental (HSE) management. The principles for barrier management were proposed by Petroleum Safety Authority Norway mainly from the operation and maintenance perspectives (PSA, 2013).

Bow tie analysis was widely used to illustrate the safety barrier concept and facilitate barrier management. Duijm (2009) proposed a safety-barrier diagram based on the bow-tie diagram and suggested it as a tool to support the management and maintenance of safety barrier systems. A study presented that a full bow tie can be developed to conduct a comprehensive risk analysis with all the associated controls identified. The frequencies of threats and the effectiveness of the barriers are quantified (Hudson & Hudson, 2015). A joint publication by CCPS (USA) and Energy Institute (UK) emphasized that safety barrier management relies on safety barriers being auditable (CCPS/EI, 2018). The same publication presented guidance on how bow ties can be used for risk management purposes through the effective depiction of barriers. Meanwhile, the use of bow ties utilizing a life-cycle approach, including barriers validity, degradation factors and degradation controls, and the involvement of human and organizational factors were discussed (Fiorentini & Marmo, 2018; CCPS/EI, 2018). The influence of human performance and factors on barrier management was investigated in previous studies (McLeod R, 2016; CIEHF, 2016). The recommendations for good practice in developing and managing human factors of barrier systems were given by the Chartered Institute of Ergonomics and Human Factors (CIEHF, 2016). A practical guidance on barrier management with a focus on maintaining barriers throughout the lifetime of an offshore or onshore petroleum facility was proposed, in which the identification of barrier elements, barrier monitor, and barrier inspection were discussed (Hauge & Øien, 2016). Van Nunen et al. (2019) suggested combining safety barriers with safety indicators to support occupational safety management, stressing the practicality and significance of obtaining barrier management from the performance/safety indicators perspective. The guidance for the management of safety–critical elements (SCEs) was proposed to prevent or limit the effects of major accident hazards (MAHs) from the assurance and verification aspects (Energy Institute, 2020). In the same study, the using

Table 5
Characterization of current researches on safety barrier assessment in the chemical process industry (before October 13th, 2021).

Publications	Methodologies	Target objects or scenarios	Investigated barriers	Other keywords
Khan et al. (2002)	SCAP: Safety, Credible Accident, Probabilistic fault tree analysis	ethylene oxide (EO) plants	flame arrester, installing insulated barrier (wall) between transportation and storage vessel, regular maintenance scheme for corrosion and other mechanical defects, sprinkling system, advanced control mechanism, advanced final control element (digital controller), installation of pressure monitoring with emergency relief system, installing cooling system, replacement of old valves with more reliable valves, check valve with relief provision, installation of additional controllers, installation of bypass line, flammable chemical detector, safety relief valve, emergency relief valve to evacuate the contents to another vessel, inert gas purging/blanking system to dilute released toxic/flammable gases	safety measures, industrial hazards, worst-case scenario, maximum credible accident analysis
Yun et al. (2009)	LOPA (layer of protection analysis) and Bayesian estimation	LNG importation terminals	one IPL involving the temperature safety valve (TSV)	risk assessment, failure data quality, probability of failure on demand (PFD), IPL
Cai et al. (2012)	Bayesian networks	petroleum drilling rig explosion and oil spill	subsea blowout preventer control system	reliability, common cause failure, imperfect coverage
Cai et al. (2013)	Bayesian networks	petroleum drilling rig explosion and oil spill	subsea blowout preventer operations	quantitative risk assessment
Pitblado & Nelson (2013)	bow tie	major accidents in Oil and Gas (O&G) and process industries	inspection program, preventive maintenance (PM), inspection or PM item, relief valve, ESD valve, gas detection device, training course, fatigue management, work permit system	\
Xue et al. (2013)	barrier-based accident model and event tree analysis	offshore drilling blowouts	primary well barrier, well monitoring barrier, secondary well barrier, ignition prevention barrier, escalation prevention barrier, emergency response barrier, blowout control barrier, oil spill control barrier	accident model, active failures
Myers (2013)	LOPA (layer of protection analysis)	accident scenarios in process industries	active protection layers involving human IPLs	process safety, human error probability, human reliability analysis, initiating event, independent protection layer
Badreddine et al. (2014)	bow tie diagram	unconfined vapor cloud explosion	implementing an employee training, storage tank inspection, infrared cameras for gas leak detection, gas detection and protection system, fire detection and protection system, carbon monoxide alarms	propagation algorithms, multi-objectives influence diagrams
Innal et al. (2014)	fault tree and Markov model	steam boiler breakup	independent and dependent protection layers, safety instrumented systems	failure frequency
Landucci et al. (2015)	LOPA (layer of protection analysis) and event tree analysis	fire-triggered domino scenarios	water deluge system, pressure safety valve, fireproofing, emergency teams	major accident hazard, quantitative risk assessment
Khakzad & Reniers (2015)	Bayesian networks	major accidents concerning domino effects	land use planning (LUP)	multi-criteria decision analysis, fuel storage plant
Ramzali et al. (2015)	event tree analysis, reliability block diagram, fault tree analysis	leakage in drilling well of offshore drilling system	barriers in operational phase.	barrier analysis
Villa & Cozzani (2016)	Bayesian networks	major accidents within the process industry	fixed foam system, rim seal fire extinguisher	\
Landucci et al. (2016)	LOPA (layer of protection analysis) and event tree analysis	fire-triggered domino scenarios	foam-water sprinkler system, water deluge system, emergency shutdown system, pressure safety valve, fireproofing coating, external emergency intervention	performance analysis, escalation frequency
Kang et al. (2016)	fuzzy mathematic theory, incident process analysis	oil storage facility explosion	personnel barriers, organizational barriers, technological barriers	accident evolution, failure mechanism
Cai et al. (2016)	multiphase dynamic Bayesian networks (MDBNs)	k-out-of-n architectures	safety instrumented systems	safety integrity level
De Souza et al. (2017)	Petri nets	modern production systems	safety instrumented system	risk analysis, scenarios of faults
Bucelli et al. (2017)	bow tie and risk barometer methodology	major accidents in the oil and gas (O&G) industry	limit hydrocarbon leak	risk assessment
Khakzad & Reniers (2017)	Bayesian networks, limited memory influence diagram (LIMID)	fire-induced domino effects	fireproofing of storage tanks	multi-attribute decision analysis
Khakzad et al. (2017a)	event tree analysis, dynamic Bayesian network	fire-induced domino effects	firefighting systems based on water supply, emergency isolation and depressurization systems, passive fire protections, emergency response	quantitative risk assessment
Khakzad et al., (2017b)	graph theory	fire-induced domino effects	fireproofing protection (passive fire protection) and active protection systems	multicriteria decision making, quantitative risk assessment
Yan et al. (2017).	LOPA (layer of protection analysis) and cloud model	gas leakage in a biomass gasification station	ventilation and alarms	Randomness, fuzziness, normal cloud major accident hazard

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Table 5 (*continued*)

Publications	Methodologies	Target objects or scenarios	Investigated barriers	Other keywords
Bucelli et al. (2018)	LOPA (layer of protection analysis) and event tree analysis	fire-induced cascading events of offshore facilities in the harsh and sensitive environment	water deluge system, emergency shut down, pressure safety valve, passive fire protection, emergency response and rescue	
Wu et al. (2018)	Monte Carlo models	subsea blowout preventer system	subsea blind shear ram preventer (BSRP)	unavailability analysis, multiphase Markov process, testing strategies
Tsunemi et al. (2019)	event tree analysis	hydrogen leaks in the hydrogen refueling station	excess flow stop valve, leak detector and shutoff valve, manual operation	quantitative risk assessment
Sobral & Soares (2019)	bow tie diagram and LOPA	a fire pumping system	sensor system, logic system, actuator system	probability of failure on demand, safety integrity level
Simon et al. (2019)	dynamic Bayesian networks (DBNs)	chemical reactor protection system	safety instrumented systems	safety system, proof tests, test strategy, test duration, probability of failure on demand
Misuri et al. (2020)	expert elicitation	Natech scenarios	active and passive barriers	performance assessment
Bubbico et al. (2020)	Bayesian networks	process leak-fire/explosion-escalation in Oil&Gas platform	leak detection, blowdown, deluge system, hydrocarbon inflow shut-off, ignition prevention, escalation prevention, passive fire protection, depress pressure safety valve	dynamic risk analysis, extreme environment
Ding et al. (2020)	bow-tie, Bayesian network models	cotton storage fire	detection and extinguishment, fire brigade	criticality analysis, risk control strategies
Zhu et al. (2020)	LOPA (layer of protection analysis) and dynamic simulations	batch reactor systems	human actions and response	human error probability, human reliability analysis
Misuri et al. (2021a)	LOPA (layer of protection analysis) and event tree analysis	domino scenarios caused by Natech events	foam-water sprinkler system, water deluge system, passive fire protection, pressure safety valve, emergency teams	escalation, mitigation
Misuri et al. (2021b)	LOPA (layer of protection analysis) and event tree analysis	domino scenarios caused by Natech events	pressure safety valve, foam-water system, water deluge system, passive fire protection (fireproofing), external emergency intervention	Natech, domino effect, escalation, quantitative risk assessment
Park et al. (2021)	LOPA (layer of protection analysis)	hydrogen refueling stations	passive IPLs: dike, underground draining system, open vent (no valve), fireproofing, blast wall or bunker, inherently safer design, flame or detonation arrestors; active IPLs: gas detector and emergency shutoff valve, relief valve/rapture disc, basic process control system	individual risk, societal risk, F–N curve, IPLs
Ovidi et al. (2021)	agent-based modelling	domino effects	fireproofing, foam/water system (FWS), water deluge system (WDS), external emergency intervention (EEI)	computational experiments, process safety, chemical tank farm
Dimaio et al. (2021)	Bayesian networks	major accident scenarios (fire, explosion, toxic dispersion)	process safety management system (PSMS), task management (TM), design integrity (DI), operating integrity (OI), process control system (PCS), pressure protection system (PPS), isolation & depressurization (I&D), fire management (FM), emergency response system (ERS), spill containment system (SCS)	quantitative risk assessment, living risk assessment, key performance indicator, probabilistic safety margins
Hosseinnia et al. (2021)	bow-tie analysis	floating, production, storage, and offloading unit (FPSO) process	Goliat safety barriers including a series of active barriers, passive barriers, human actions, and symbolic barriers	oil and gas, offshore platforms, dynamic risk analysis, risk-based inspection, accident prevention
Sun et al. (2021)	Bayesian networks	wax oil hydrogenation process	prevention barrier (RPB), dispersion prevention barrier (DPB), ignition prevention barrier (IPB), escalation prevention barrier (EPB), damage control emergency management barrier (DCEM), human factor barrier (HFB), management and organizational barrier (MOB)	resilience, availability

safety integrity level (SIL) determination to set and measure performance targets in performance standards (PSs) was suggested and the guidance on SCE continual improvement, managing SCE aging, obsolescence, and life extension was proposed. The challenges and clarifications of the central concepts and steps in barrier management were discussed (Johansen & Rausand, 2015). The integration of quantitative risk assessment and risk barometer methodology was suggested to support barrier management by reflecting barrier status concerning technical features and operational and organizational activities related to barriers (Bucelli et al., 2017). The principles for barrier status and associated risk monitoring in the operational phase were outlined by a handbook (Hauge et al., 2015). Then, the concept of dynamic barrier management (DBM) was proposed to achieve barrier maintenance optimization based on quantitative barrier importance to risk control, like risk-based inspection (RBI) (Pitblado et al., 2016; Hosseinniaa et al., 2019). Zhen et al. (2021) proposed a multi-objective optimization approach for preventive maintenance (PM) of safety–critical barriers, in which the optimum PM intervals were determined by risk assessment and maintenance cost evaluation.

From the design or allocation perspective, Reniers et al. (2008) proposed a user-friendly decision-support tool integrating safety and security to prevent domino effects in chemical clusters. Based on metaheuristics, a decision model was proposed to allocate protective safety barriers with limited budgets and mitigate domino effects (Janssens et al., 2015). A graph-theoretic approach was proposed to achieve an optimal firefighting strategy to prevent or delay fire-induced domino effects in fuel storage plants (Khakzad, 2018). Additionally, cost-effectiveness analysis was widely used in the optimization or optimal allocation of safety and/or security barriers. A methodology based on graph theory and multi-criteria decision analysis was proposed to analyze the impacts of both the availability and the degradation of safety barriers on the vulnerability of chemical plants and support decision-making on allocating fire-protection barriers (Khakzad et al., 2017b). An approach was developed based on BN and limited memory influence diagram to assess the impacts of safety barriers on the propagation of fire-induced domino effects and obtain the cost-effective allocation of add-on safety barriers (Khakzad et al., 2018). A consequence-based method was established to optimize the allocation of safety and security resources in chemical industrial parks concerning intentional attacks, in which the security measures and safety barriers were integrated into a dynamic vulnerability assessment graph (DVAG) model for vulnerability assessment of installations (Chen et al., 2019). Cincotta et al. (2019) proposed an approach for optimizing firefighting strategies to increase the resiliency of process plants in dealing with fire escalation scenarios. The net present value of benefits (NPVB) and the "PROTOPT" optimization algorithm were employed in an economic analysis to determine the most profitable protection strategy with the combination of safety and security measures (Chen et al., 2020). Moreover, Xing et al. (2020) proposed a joint optimization model to synthetically optimize safety barriers considering both business continuity and accident prevention in the case of steam generator tube rupture accidents in nuclear power plants. Ovidi et al. (2021) developed an agent-based model which can be employed to assess complex domino events and support the decision-making on the allocation of safety barriers in chemical process industries.

Apart from optimizing add-on safety barriers, the strategies for the optimization of inherent designs were also investigated. Bayesian networks and conflict analysis were employed to obtain a risk-based allocation of chemical inventories considering dynamic consequence analysis of domino effects (Khakzad et al., 2014). Additionally, land-use planning (LUP) was regarded as an effective and crucial safety measure in the risk management of major hazard installations. Khakzad & Reniers (2015) proposed a BN-based methodology to assess both on-site and off-site risks of significant accidents and obtain the risk-based design of chemical plants by using Analytic Hierarchical Process (AHP). The BN was employed for the cost-effective allocation of safety measures in chemical plants concerning LUP requirements, which was used as an inherent safety measure in the risk management of chemical plants (Khakzad & Reniers, 2017). Furthermore, an approach based on inventory management on chemical loading/unloading demands was proposed to determine the optimal risk management strategy for fire-induced domino effects (Ding et al., 2021).

5.2. Knowledge and technical gaps of barrier management

Based on the above studies related to barrier management, we found that although the concept of safety barrier has been applied in chemical process industries for a long time, challenges still exist in the management and optimal allocation of safety and/or security barriers. This paper has identified the primary knowledge and technical gaps as follows:

- Previous studies mainly focus on the performance assessment and optimization of safety and/or security barriers. The performance indicator-based barrier management needs further investigation. Particularly for the non-technical safety barriers, the identification of performance indicators and the practical evaluation of safety barriers based on quantitative risk assessments are still challenges.
- Current models or approaches for safety barriers management or optimization mainly focus on preventing fire-related accidents, especially fire-induced domino effects. In contrast, the research about implementing and managing safety barriers in other hazards, such as poisoning and suffocation, mechanical injury, and electric shock, is lacking.
- Existing safety barrier modelling and optimization approaches are limited to relatively straightforward scenarios, sometimes different from real accident scenarios. Besides, safety barriers can interact with the environment, accident scenarios, and human operations, bringing considerable difficulties to the safety barrier modelling and optimization. Therefore, new techniques and methods should be developed to tackle complex accident scenarios.
- The design, installation & operation, and management of safety barriers is systematic work. The operation of a safety barrier may cause some interventions to other safety barriers. Most studies focus on the type of decompositional or reductionist approaches, which deal with the individual contribution of safety barriers to risk management of chemical plants. A knowledge gap exists in how systemic risk can be minimized through safety barriers management.

6. Recommendation for future works

According to the review of definition, classification, performance assessment, and management of safety barriers in the chemical and process industry. Some promising research directions and challenges for future work were illustrated in this section.

6.1. Integrated management of safety and security barriers

Process facilities are inevitably exposed to accidental and intentional risks. Thus, security management is an indispensable component of the process risk management. The risk analysis of potential catastrophic accidents caused by intentional and malevolent acts was highly stressed (CCPS, 2003), and it's of significance to conduct a risk analysis considering both safety and security risks due to the interactions between safety and security (Song et al., 2019b). As essential measures to prevent, control, or mitigate undesired events, barriers used for safety and security purposes with significance to be integrated and managed in a systematic framework. Although the assessment and management of security barriers were also investigated in previous studies (Mcgill et al., 2007; van Staalduinen et al., 2017; Song et al., 2018), a systematic management procedure for integrating safety and security barrier has not been developed yet. Therefore, we suggest the methodologies and models targeting integrated management of safety and security barriers need to be developed.

Because the inter-dependency exists between safety and security (Song et al., 2019a), the performance of both safety barriers and security protection measures should be assessed comprehensively within the consideration of the inter-dependency between safety and security. Meanwhile, the independence of barriers should be studied and promoted to reduce the probability of the occurrence of undesired events induced by adverse interventions between safety and/or security barriers. The aspects of safety and security management, including barrier identification, barrier classification, performance indicators and information collection, barrier performance assessment, barrier maintenance, and barrier allocation and optimization, are expected to be designed and operated coordinately. The comprehensive risk analysis and decision model considering both safety and security aspects are needed further studied to support decision-making and safety and security barrier allocation and management in the chemical and process industry.

6.2. QRA-based management of barriers

Quantitative risk assessment (QRA) is regarded as a valuable tool and promoted to improve risk management through identifying major risk contributors and various risk reduction options in process industries (Freeman, 1990; Stoffen, 2005). However, the implementation of QRA regarding barrier assessment and barrier management is still challenging. Previous studies mainly investigated the failure probabilities of barriers (Landucci et al., 2015; Khakzad et al., 2017a), such as PFD, which benefits the quantitative frequency/probability analysis of the risk assessments. By contrast, the quantitative consequence assessment is seldom obtained due to the difficulties in integrating the interventions from barriers into the consequence assessment. Besides, barriers degradation and dependencies are also significant in the quantitative assessment of barriers (Dimaio et al., 2021; Misuri et al., 2021b), which supports the QRA-based barrier optimal allocation and is worthy of further investigation.

From the barrier maintenance perspective, risk-based barrier maintenance was suggested to achieve better barrier inspection and repair at a lower cost (Pitblado et al., 2016). QRA benefits barrier maintenance by determining those barriers that contribute most to major accident risk reduction. Thus the barriers with higher importance to risk reduction could be assigned a higher priority than other barriers (Hosseinniaa et al., 2019). However, the qualitative or semi-quantitative risk assessment methods, such as bow-tie, cannot directly show the importance of individual barriers. QRA-based barrier maintenance approach should be developed to optimize barrier maintenance. Therefore, the quantitative assessment of barrier performance and further barrier management based on QRA is a promising research area that can benefit both risk-based barrier maintenance and decision-making on barrier optimal allocation.

6.3. Resilience-based management of barriers

The application of the resilience concept under the process safety domain has already been suggested in previous studies due to its advantages in targeting complex socio-technical systems (Castillo-Borja et al., 2017; Ham, 2020; Bento et al., 2021). However, the current practice of resilience concept concerning barrier management is still lacking. This is because safety practitioners' understanding of the resilience concept is not insightful, and the practical approaches that support the implementation of the resilience concept in barrier management are limited.

As mentioned in this paper, a barrier system can consist of technical facilities and non-technical human actions, typically a resilient system. Resilience can be regarded as a kind of comprehensive ability that reflects various capacities of a system. However, some capacities of a barrier system have not received enough attention, such as the adaptability and recoverability of a barrier system are seldom investigated in previous studies. To meet the needs of resilience-based assessment and management of process industries, it's necessary to adopt the resilience concept into the barrier assessment and barrier management domain. Although some preliminary studies attempted to involve the resilience concept in the performance assessment of safety barriers (Cincotta et al., 2019; Sun et al., 2021), the quantitative resilience assessment of barriers and further systemic management of barriers still need in-deep investigations. We suggest several aspects should be improved regarding resilience-based management of barriers. i) Some efforts can be made on developing dynamic quantitative resilience assessment methodologies targeting barrier systems. ii) A resilience-based management system needs to be developed to tackle the inspection and maintenance of safety barriers considering the operations during the whole resilient process. iii) The principles for barriers design should be investigated, and the approaches for barrier optimization and optimal allocation need to be improved from a resilience perspective.

6.4. Data-driven intelligent management of barriers

With the development of big data and artificial intelligence techniques, the landscape of safety and security in the chemical and process industry has dramatically changed. On the one hand, the assessment and management of automatic or even intelligent control systems are different from traditional barrier assessment and management, such as the digital and cyber-security issues become new threats to process safety (Moreno et al., 2018a). On the other hand, the data-driven intelligent approaches with potentials to support safety management by extracting and utilizing massive performance-indicator-related data of barriers from various sources. For instance, the data-driven approach helps plant operators and engineers to deal with complex tasks like process monitoring, fault detection, and diagnosis, and maintenance optimization (Stluka & Mařík, 2007; Jain et al., 2019). Multiple data sources are suggested to be employed to determine near-real-time barrier status (Pitblado et al., 2016).

Accordingly, the methodologies used in all the stages of barrier management need to be updated by involving new techniques and intelligent equipment. The enhancement of barrier performance through applying intelligence techniques and the intelligent collection and analysis of informative data through building data warehouses targeting safety and security barriers are expected to benefit the management of safety and security barriers. The monitoring, inspection, maintenance, performance assessment, and management of safety and security barriers are expected to become automated and intelligent through utilizing artificial intelligence techniques and achieving data-driven management.

7. Conclusions

This paper presents a systematic review of the history, definition, classification, performance assessment, and management of safety barriers in chemical process industries. Although the literature has contributed tremendously to implementing and managing safety barriers, many endeavors are needed to develop an integrated and resilient safety and security barrier management system.

Based on the literature study, the definitions of safety barriers can be divided into a classical definition and an extended definition. The defence-in-depth concept was applied to extend the concept of safety barrier covering both physical and non-physical items. The collection and analysis of safety indicators play essential roles in evaluating safety barriers and are overlooked to some extent in previous studies. This study proposes a practical classification of safety barriers concerning safety indicators identification and assignment. According to the relationship between safety performance indicators and safety barriers, the safety barriers are classified into technical, non-technical observable, and non-technical non-observable. Additionally, safety barrier functions were determined according to five resilience stages (anticipation, monitoring, response, recovery, learning), contributing to proactive safety management. The evaluation criteria of safety barriers concerning the integration of the resilience concept were suggested. Adaptability and recoverability were added as evaluation criteria to present the effectiveness and availability of safety barriers from a time-dependent perspective.

Although the management and optimal allocation of safety and/or security barriers have been focused on in previous studies, a comprehensive safety and security barrier management procedure has not yet been developed, which should involve barrier identification, barrier classification, indicator-related data, information collection, barrier performance assessment, and barrier allocation and optimization. This paper drives future research focus on safety and security-integrated management, resilience-based barrier management, and data-driven management.

CRediT authorship contribution statement

Shuaiqi Yuan: Conceptualization, Methodology, Formal Analysis, Investigation, Writing – original Draft, Review & Editing. **Ming Yang:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Genserik Reniers:** Supervision, Writing – review & editing. **Chao Chen:** Writing – review & editing. **Jiansong Wu:** 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.

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