Reliability Engineering and System Safety 160 (2017) 37–53

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Risk assessment of mitigated domino scenarios in process facilities

Gabriele Landucci[a], Amos Necci[b], Giacomo Antonioni[b], Francesca Argenti[b], Valerio Cozzani[b,*]

[a] *Dipartimento di Ingegneria Civile e Industriale, Università di Pisa, Largo Lucio Lazzarino n. 2, 56126 Pisa, Italy*
[b] *LISES - Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Alma Mater Studiorum - Università di Bologna, via Terracini n. 28, 40131 Bologna, Italy*

ARTICLE INFO

Keywords:
Domino effect
Cascading events
Quantitative risk assessment
Safety barriers
Consequence analysis

ABSTRACT

The propagation of accidents among process units may lead to severe cascading events or domino effects with catastrophic consequences. Prevention, mitigation and management of domino scenarios is of utmost importance and may be achieved in industrial facilities through the adoption of multiple safety layers. The present study was aimed at developing an innovative methodology to address the quantitative risk assessment (QRA) of domino scenarios accounting for the presence and role of safety barriers. Based on the expected performance of safety barriers, a dedicated event tree analysis allowed the identification and the assessment of the frequencies of the different end-point events deriving from unmitigated and partially mitigated domino chains. Specific criteria were introduced in consequence analysis to consider the mitigation effects of end-point scenarios deriving from safety barriers. Individual and societal risk indexes were calculated accounting for safety barriers and the mitigated scenarios that may result from their actions. The application of the methodology to case-studies of industrial interest proved the importance of introducing a specific systematic and quantitative analysis of safety barrier performance when addressing escalation leading to domino effect.

1. Introduction

The propagation of accidents among process units may lead to severe cascading events with catastrophic consequences, usually identified as “domino effects” [1,2]. The most severe accidents occurred in the framework of chemical and process industry in the last decades presented these features [3–6]. The growing public concern about this type of events, associated with their high severity, led to important efforts in the prevention, mitigation and management of domino effects [7–10]. The development of methods and models for the quantitative assessment of the contribution of domino scenarios to industrial risk in chemical and process sites was the aim of several dedicated technical and scientific studies [2]. Technical standards [11–13] and legislation concerned with the control of major accident hazard [14] included measures to assess, control and prevent the occurrence of escalation events. The introduction of different protection layers or safety barriers is proposed [15], aimed at reducing the likelihood and/or magnitude of domino effects.

Although the role of safety barriers in the management and control of industrial risk is widely recognized, the quantitative assessment of their effect on the control and mitigation of risk due to domino scenarios was seldom addressed. Actually, the early studies concerning domino effect, carried out between 1980 and 2000, did not consider the possible prevention and/or mitigation due to safety barriers, since based on conservative and oversimplifying assumptions [16–21]. Even the more recent advanced tools based on quantitative risk assessment procedures [22,23], Monte Carlo simulations [24], graphs metrics [25], and Bayesian networks [26,27] do not include a systematical assessment of safety barrier performance in the prevention of escalation. Recently, Janssens et al. [10] proposed a model for the allocation of safety barriers for the prevention of escalation based on cost criteria. Landucci et al. [28,29] proposed a method to quantify the performance of safety barriers introducing the dual concept of availability and effectiveness, but did not address the issue of risk reduction due to safety barrier expected performance.

The aim of the present study was to extend the procedure for the quantitative assessment of industrial risk caused by domino scenarios in order to include the role and performance of safety barriers. The methodology for quantitative risk assessment of domino scenarios presented by Cozzani and coworkers [30–32], based on the four conventional steps of quantitative risk assessment (identification, frequency assessment, consequence assessment and risk calculation), was upgraded introducing specific steps addressing the expected performance of safety barriers. Risk reduction associated with safety barrier performance was assessed considering both the reduction in the likelihood of escalation and considering the possible mitigation of

* Corresponding author.
E-mail address: valerio.cozzani@unibo.it (V. Cozzani).

http://dx.doi.org/10.1016/j.ress.2016.11.023
Received 30 August 2016; Received in revised form 20 November 2016; Accepted 25 November 2016
Available online 30 November 2016
0951-8320/

secondary scenarios caused by domino effect. Several industrial case studies were analyzed in order to show the potentiality of the improved quantitative risk assessment (QRA) method and to provide indications on the expected role of safety barriers in the control of risk due to domino scenarios.

2. Safety barriers for domino effect prevention and mitigation

Technical and procedural measures, which constitute the safety layers needed to reduce the risk of accident propagation, are systematically applied in different chemical and process facilities where hazardous substances are stored, processed and transported. Reniers and Faes [33] report a list of the possible technological solutions that can be used for managing and/or preventing domino effects and discuss procedural and managerial aspects related to domino risk reduction. Safety layers may be classified according to CCPS (Center of Chemical Process Safety) [15] in four categories: i) inherently safer design; ii) passive protection systems; iii) active protection systems; iv) procedural and emergency measures.

The inherent safety approach is based on actions aimed to achieve process safety by a reduction or, eventually, the elimination of the hazard through the adoption of inherent safety technologies (IST).

The introduction of appropriate safety distances between the more hazardous process units is an example of possible application of IST, during the design phase and layout definition of an industrial facility. However, easiness of access for emergency operations and/or the reduction of unnecessary complexity in the layout plot, represent key elements associated with the inherently safer design of plant arrangement.

In a wider perspective, the overall process design phase is characterized by the possibility to change parameters, such as operative and storage conditions, equipment design, and inventories leading to the adoption of inherent safety principles (see [34–36] for more details). The reduction of the inventory in single equipment items or of the number of equipment items may have a strong impact on the reduction of the hazard, since inventory affects the magnitude of secondary fires and explosions. The hazard may be also reduced in case of adoption of materials featuring less hazardous properties. The use of less hazardous operating conditions (for example, reducing storage pressure, preferring cryogenic instead of pressurized storages, etc.) is effective in reducing, on the one hand, the hazard of the primary event and, on the other, the vulnerability of possible target equipment and the severity of the possible escalation scenarios [37].

This type of approach is extremely effective [7] but its application is mostly limited to early design steps when dealing with the prevention of escalation [34,37–39] and relevant modifications may conflict with other drivers of the design phase (costs, use of well-known technologies, standardization, etc.). Thus, the present study focused on passive, active and emergency measures.

Passive systems do not require external activation to perform the protective action. A typical example is the application of a heat resistant insulation on process equipment in order to reduce the incoming heat flux due to fire, and, consequently, the vessel heat-up [40–44]. This allows to delay the time to reach the critical conditions leading to the failure of the exposed target [40,45]. Another widely applied type of passive fire protection system consists of an emergency relief device, such as a pressure safety valve, aimed at avoiding the pressure build up and consequent mechanical stress increment in equipment exposed to the fire [46–49]. Passive protection can also be effective for mitigation in domino chains involving blast waves or fragments as propagation vector, through the installation of blast walls or mounds [50–52], aimed at reducing peak overpressure and impulse on the protected targets.

Active systems require external automatic and/or manual activation; hence feature lower robustness than passive systems. Nevertheless, they may be effective and are often compulsory in technical standards [11,12,53,54]. Active protections may be aimed either at preventing or mitigating domino effect. Emergency shutdown (ESD) and emergency blowdown (EBD) are usually adopted to prevent domino effect reducing the escalation potential of the primary scenarios [48]. ESD systems act isolating the process units, thus reducing the severity of fires and vapor cloud explosions (VCEs), by limiting the inventory of released flammable materials. EBD systems depressurize the process units venting their content to the flare, thus reducing the potential loss and the pressure in the target equipment.

Active mitigation barriers may as well aim at protecting the target from the effects of the primary event. Typical examples are water deluge systems (WDS) and foam/water sprinklers [55–57]. WDS mitigate the fire exposure of the target, providing a water film on the exposed surfaces to absorb radiant heat and to lower the temperature of the metal shell, thus preventing loss of strength. They are typically installed on pressurized vessels (e.g., separators, horizontal storage units, pressure buffers, etc.) [56]. Sprinkler systems instead may provide an effective control of the primary fire and may prevent fire spread in nearby units delivering fire-fighting agents such as water or foam. Sprinklers are typically installed on atmospheric storage vessels [58].

Since active mitigations typically have a significant time lag of intervention, mitigation actions aimed at protecting the target vessels are usually ineffective for primary scenarios as fireballs (which feature characteristic time ranges typically between 1 and 20 s [45,48,59]) and overpressure due to VCEs or mechanical explosions (that are phenomena lasting few tens to hundreds of milliseconds). These times are typically less than characteristic response times of any active protection equipment [60].

Finally, procedural and emergency measures may support the management and control of scenarios having an escalation potential by their integration with passive and/or active measures [48]. Emergency response can be provided by internal and/or external emergency teams [48]. These teams can be composed of expert fire-fighters as well as of volunteers or workers who receive a specific training. For this type of barriers, the characteristic response time may be longer by one or two orders of magnitude compared to active measures. Therefore, no procedural measures are usually applicable to fast evolving scenarios (fireball, mechanical explosions, VCE, etc.). However, emergency management of scenarios involving steady fires (e.g., pool or jet fires) can be crucial in preventing escalations.

3. Methodology

3.1. Overview

The quantitative assessment of safety barrier performance is a critical task for the sound estimation of escalation hazard and a specific methodology was introduced to account for the above described safety barriers in the quantitative assessment of the risk associated to domino scenarios. Fig. 1 shows the procedure for the quantitative assessment of risk due to domino scenarios (Fig. 1a) and the approach to include the performance of safety barriers it in the final risk figures (Fig. 1b). As shown in Fig. 1a, the baseline methodology developed by Cozzani et al. [30–32] was modified introducing a specific step to account for the possible preventive effect due to the presence of safety barriers.

The starting point of the methodology (step 1 in Fig. 1a) is the identification of reference equipment which may lead to a Loss Of Containment (LOC) event able to generate primary events resulting in escalation. After the reference equipment identification, in step 2 the analysis is focused on the selection of the primary event, which is characterized both in terms of expected frequency and of consequences. This allows defining the “escalation vector” in step 3, that may impact on the nearby equipment. Then, in step 4, the identification of potential targets is carried out by a threshold-based approach