

Assessing the Impact of Natural Hazards on Safety Barriers on the Basis of Expert Elicitation

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Natural hazards pose critical threats to chemical and process installations handling hazardous materials. In particular, severe technological accidents involving the release of chemicals can be triggered by natural events, namely Natech accidents. Moreover, natural hazards can impact and weaken safety measures for accident prevention and mitigation implemented in the impacted plant, increasing the credibility of severe domino effect escalation and, thus, affecting the risk induced by Natech scenarios. The present study is aimed at developing a structured approach aimed at supporting the probabilistic evaluation of Natech events in presence of safety barriers. Barrier performance are described with a specific metric, able to quantitatively assess the degradation due to natural hazards. The methodology is applied to the analysis of an industrial case study, showing the influence of the natural event impact on the performance of safety barriers and, thus, on the probability and frequency of escalation scenarios triggered by Natech events.

1. Introduction

In the last decades, natural hazards became a reason of concern for the safety of chemical and process installations (Krausmann et al., 2017). Indeed, the impact of natural disasters can lead to the release of hazardous substances that are usually handled in such installations. These technological accidents, arising from the interaction between natural causes and process installations are usually referred to as Natech events and can be particularly critical (Krausmann et al., 2017). In fact, severe natural events, such as earthquakes, floods or storms have an impact over a wide area and may damage multiple items located in the plant, leading to simultaneous scenarios.

Another critical aspect of Natech accidents is the possibility that systems in place in the plant for accident prevention and mitigation are concurrently damaged and not able to perform their function. This issue was critical during Hurricane Harvey, which caused multiple chemical releases in principal refinery US areas in 2017 (Misuri et al., 2019a). For instance, a well-known accident was caused in a peroxide storage in Crosby due to the loss of electricity and unavailability of backup generators led by the storm-related flooding (CSB, 2018). Again, during Koaceli earthquake (1999), fires arising from petrochemical storage spread over wide areas since many firefighting installations were unavailable due to water lifeline disruption and power outage leading to pumps unavailability, and massive quantity of toxic materials was released into the sea due to containment dike structural failure due to strong ground shaking (Girgin, 2011).

Therefore, assessing the risk associated with Natech scenarios in chemical and process facilities is of utmost importance and represents a critical task. Methodologies to carry out the quantitative risk assessment (QRA) of Natech scenarios in process facilities are available in the literature (Cozzani et al., 2014). However, the role of accident prevention and mitigation systems, i.e., safety barriers, and the influence of their possibly reduced performance caused by the impact of natural events is not assessed (Antonioni et al., 2015).

The aim of the present study is to develop a novel methodology for assessing the impact of natural hazards on safety barriers, with the final aim of the inclusion on risk assessment procedures. The methodology is based on expert elicitation to obtain barrier performance modification factors. Frequency of escalation is then modelled by means of event tree analysis specifically developed to assess domino propagation. The methodology is applied to an industrial case study.

2. Methodology

The conceptual framework for the methodology is presented in Figure 1, based on the approach developed by Misuri et al. (2020). The preliminary element is definition of the natural events under concerns (Step 1), which influence the type of damage associated with the impacted process equipment and safety barriers. Safety barriers are then classified in categories sharing similarities (Step 2), and a suitable metric for barrier performance evaluation is defined (Step 3). Information on the impact of natural hazards on barriers are retrieved from expert elicitation procedure (Step 4), expressing the main findings by means of performance modification factors (Step 5). Finally, these factors are implemented in the performance assessment metrics (Step 6), with the final aim of including degraded barriers in event tree analysis to evaluate how final scenario frequencies are modified (Step 7). The steps of the methodology are thoroughly described in the next sections.

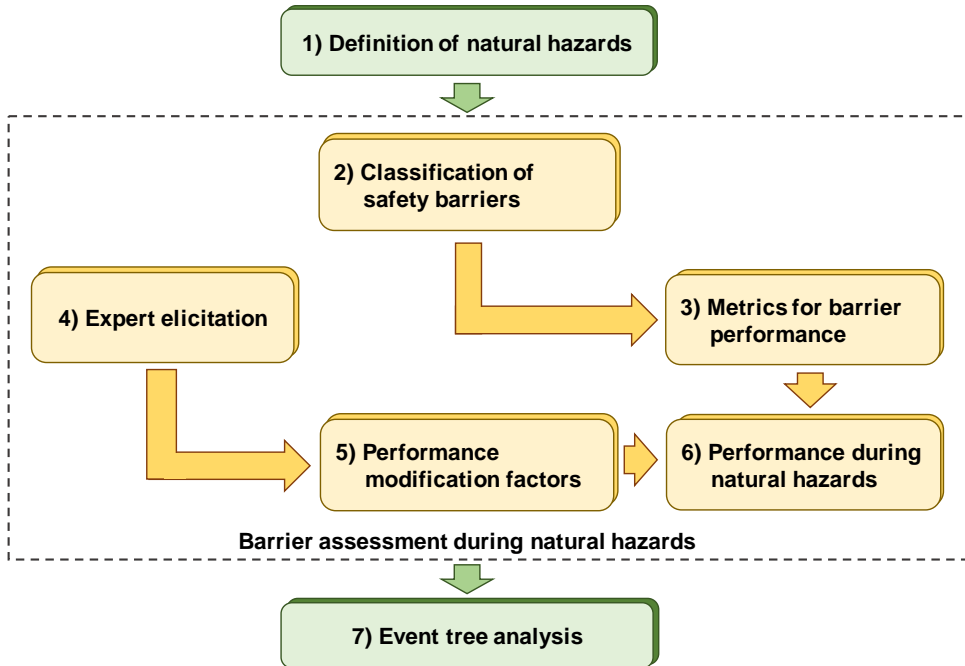


Figure 1: Conceptual framework for safety barrier assessment during natural hazards.

3. Safety barriers analysis: conventional approaches

3.1 Basic concepts and classification

Safety barriers represent the conceptualization of technical and organizational measures for accident prevention or consequence mitigation, which are commonly implemented in chemical and process plants (Delvosalle et al., 2006). Safety barriers are the means for performing safety functions they are designed for (PSA, 2013), such as reducing heat radiation affecting a target equipment, containing a liquid spillage, depressurizing equipment, etc. Several definitions have been given in the literature, embracing a great variety of fields (Sklet, 2006).

In the present work a well-established classification for barrier based on working-principle, that is in the way the safety function is expressed. Hence, safety barriers may be divided in three main categories (CCPS, 2001):

- Passive barriers: physical measures permanently in place in the plant that do not require external of activation to perform their safety functions; containment bunds, catch basins, fireproofing materials are relevant examples of barriers belonging to this category;
- Active barriers: complex instrumented systems requiring activation to perform their safety functions; most of firefighting network systems belong to this category, as well as emergency shutdown (ESD);
- Procedural barriers: procedures and coordinate operations carried out by internal personnel or external intervention; emergency intervention of fire brigades is a relevant example of barrier of this group.

3.2 Performance assessment of safety barriers

In this work, a two-parameter metrics has been adopted to characterize barrier performance. The metrics has been specifically developed in the framework of risk assessment of mitigated domino scenarios (Landucci et al., 2017). Overall barrier performance in accident mitigation are thus described by means of a probability of failure on demand (PFD), expressing the probability that the barrier when required to perform its safety function fails, and a parameter expressing the likelihood of successful escalation prevention once activated, namely an effectiveness (η). For the case of passive barriers, PFD is not required, since are permanently performing their function without the need of external activation.

This metrics has been obtained from layer of protection analysis (LOPA) approach, which is widely adopted within industry for safety barrier characterization (CCPS, 2001). It should be noted that in the original methodology η was not assessed, while it is critical in domino accident assessment (Landucci et al., 2016). Values of PFD and η for common safety barriers can be found in previous works, see e.g. (Landucci et al., 2015) and references cited therein. In case data is not directly available, performance values can be obtained via the application of reliability techniques (e.g., fault tree analysis), starting from reliability database entries for component availability (Mannan, 2005).

4. Safety barrier performance during natural hazards

4.1 Expert elicitation

Due to the scarcity of statistical data to be used as basis for barrier performance tailorization, an expert elicitation was performed, involving more than 40 experts in the field (Misuri et al., 2020). Experts were asked to express quantitative judgments on the barrier failure likelihood considering earthquakes and floods of plausible intensity. Supplementary information on terminology and technical schemes to consider was also provided to the experts. The analysis was limited to two natural hazards only, both because those are the events with the potential of causing most severe accidents (Krausmann et al., 2017), and to facilitate answering. Nevertheless, the same approach can be adapted to other natural hazards. Figure 2a and Figure 2b report the distributions of probability of damage due to natural hazards elicited from the experts for floods and earthquake, respectively (Misuri et al., 2020).

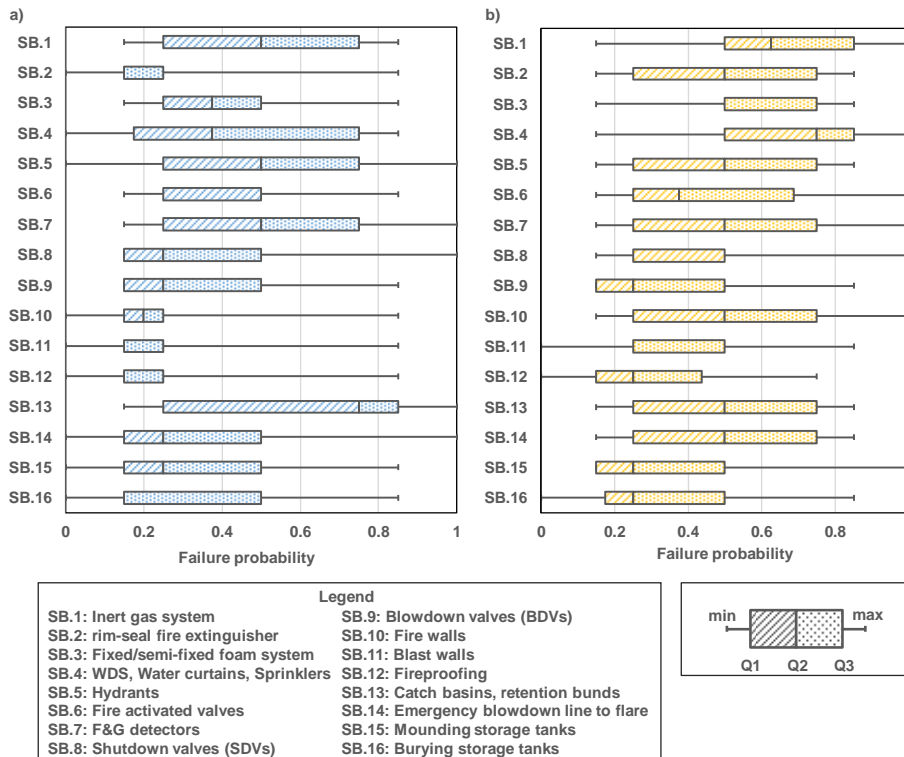


Figure 2: Elicited distribution for barrier failure probability due to a) floods and b) earthquakes. Boxplot terminology: min=minimum value, Q1=1st quartile, Q2=2nd quartile (median), Q3=3rd quartile, max=maximum value. Based on (Misuri et al., 2020).

4.2 Performance modification

The median value (Q2 in Figure 2) has been chosen as performance modification factor (ϕ_n) describing the direct impact of n-th natural hazard on barriers. The choice of the median as representative indicator of elicited distributions is in agreement with previous studies, as discussed elsewhere (Misuri et al. 2020). Considering past accident analysis, some failure patterns were identified (Misuri et al., 2019b). In particular, the dependence on lifeline of active barriers may be a critical flaw during natural hazards (Misuri et al., 2019a). Indeed, these high impact events may affect broad areas and cut lifelines and services like power connection (Karagiannis et al., 2017). Backup generators may be vulnerable as well and past accidents demonstrated that there is the concrete possibility they fail during natural disasters (Labib and Harris, 2015).

Given the lessons learnt from accident analysis, it is clear that it can be assumed that the most significant contribution of natural hazards to active barrier unavailability will be linked to the lack of activation, while in case of passive barrier the system can be supposed to be structurally damaged, and unable to fully perform the design safety function. Therefore, the performance of safety barrier starting from PFD_0 and η_0 , namely the baseline probability of failure on demand and effectiveness, estimated without the contribution of natural hazard, should be assessed according to Table 1. As can be seen from the table, for the case of active barriers, the probability of failure of demand is thus updated to PFD_n to include the additional contribution of natural hazards to unavailability, while for the case of passive barriers the possible structural damage is assessed through the reduction of effectiveness to η_n . It should be noted that the methodology does not directly address procedural barriers due to their high site-specificity.

Table 1: Methodology for barrier performance modification.

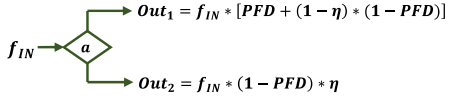
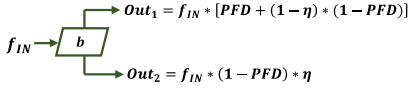
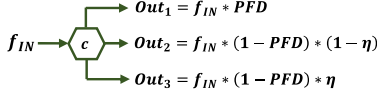
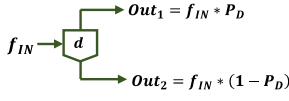
Barrier category	Modified PFD during n-th natural hazards (PFD_n)	Modified η during n-th natural hazards (η_n)
Active	$PFD_n = 1 - (\phi_n - 1) * (1 - PFD_0)$	$\eta_n = \eta_0$ (Not modified)
Passive	0 (Not modified)	$\eta_n = (1 - \phi_n) * \eta_0$
Procedural	Site-specific assessment	Site-specific assessment

5. Probabilistic assessment

The probabilistic assessment of domino scenarios developing from Natch primary accident can be carried out applying a customized event tree analysis (ETA) methodology for modelling safety barrier impact on escalation scenario frequencies (Landucci et al., 2016).

The logical operators adopted in this framework are presented in Table 2. The proper gate choice for a specific barrier is performed according to barrier functioning, as described elsewhere (Landucci et al., 2015).

Table 2: Logical operators adopted in the ETA, adapted from (Landucci et al., 2016).

Gate	Graphical representation & Combination rules	Description
a		Simple composite probability: unavailability, expressed as PFD, is combined with a single probability value for η .
b		Composite probability distribution: unavailability, expressed as PFD, is combined with a probability distribution expressing η . An integrated PFD can be used, obtaining the rule reported.
c		Discrete probability distribution: depending on barrier η , three events may arise.
d		Vessel fragility gate: the failure probability is calculated accounting for the status of the target equipment (e.g., received heat load).

As shown in the table, four types of operators are considered and graphically depicted as gates. Safety barriers can be described by means of “a” and “b” gates, representing composite probabilities, which are combinations of both the probability that barrier is not activated on demand and that is not able to perform the required safety function effectively (i.e., the two performance parameters, PFD and η , respectively). Thus, Out_1 is the frequency of failure in mitigation, given the frequency entering the operator f_{IN} , and Out_2 quantifies the frequency of success. Gate “c” is used to model emergency intervention, and it is associated with a discrete probability distribution since multiple outcomes are considered, according to the value of η . Lastly, gate “d” is included to model equipment vulnerability to escalation. The probability of failure (i.e., P_D in Table 3) depends on the escalation vector impacting the target and is quantifiable with well-established failure correlations (Landucci et al., 2009).

6. Results and discussion

In order to show the application of the methodology, a simple example is defined. The possible domino escalation due to primary fire radiation on an atmospheric storage tank is considered. The target vessel is assumed to store a flammable substance (e.g., gasoline), and a reference frequency of $f_i=1.0e-5 y^{-1}$ for the primary fire is considered. Tanks storing these hazardous substances are usually provided of foam water systems for fire extinction (SB.3 in Figure 2) and catch basins for flammable liquid spreading prevention in case of loss of containment (SB.13 in Figure 2). The effect of both floods and earthquake is assessed, by implementing the factors shown in Figure 2 to modify PFD and η of the two barriers according to the rules reported in Table 1.

The ETA applying the described methodology and the gates defined in Table 2 is shown in Figure 3. The original barrier performance is indicated with the subscript “0”, while the cases of floods and earthquakes are indicated respectively with “f” and “e”.

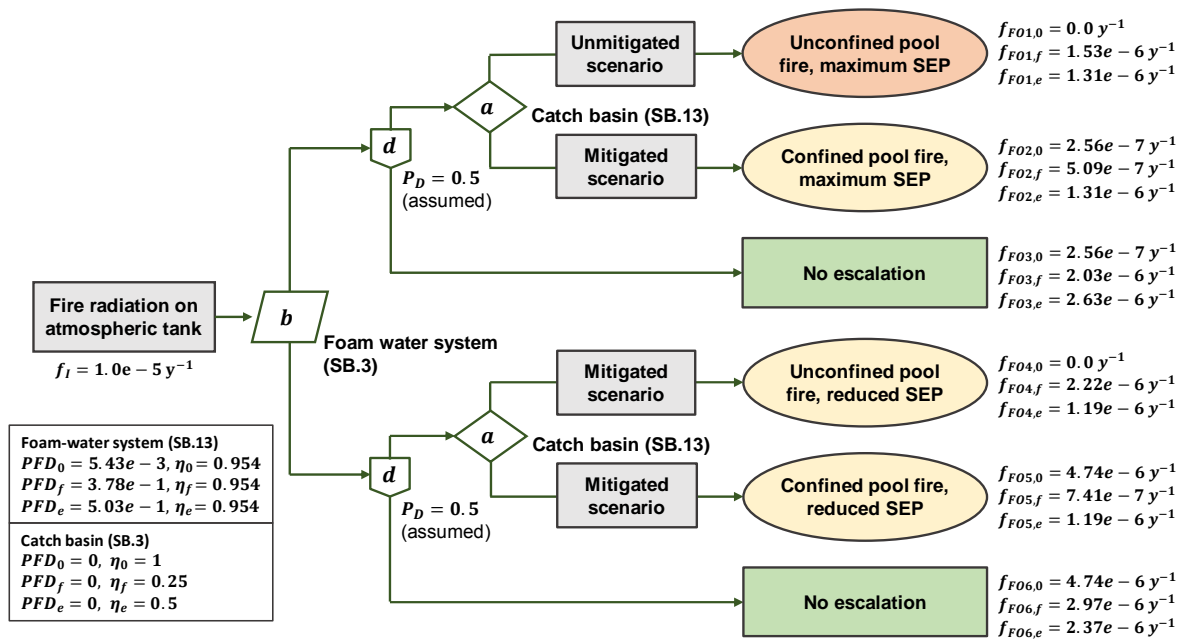


Figure 3: Example of ET for atmospheric tank impacted by heat radiation. Legend: 0=normal barrier performance, f=performance during flood, e=performance during earthquake, FO=final outcome, SB=safety barrier (for safety barriers numbering see Figure 2).

As can be noted, the concurrent degradation of barriers during natural hazards causes an increase in frequencies of the more severe final scenarios (i.e., uppermost branches). For instance, unconfined pool fire with maximum surface emissive power (SEP) is not deemed possible in case catch basin retains their original performance, while due to natural hazard impact on barriers it is a credible scenario.

7. Conclusions

In this work, a methodology for safety barrier assessment during natural hazards is presented. The methodology is based on the application of performance modification factors obtained from failure distributions from expert elicitation. A two-parameter metrics has been adopted to model barrier performance and parameters are modified according to failure patterns observed in past accidents. Barriers with modified performances are implemented in modified event tree analysis to show the influence of their degradation in the frequency of final scenarios arising from escalation of Natech scenarios. The methodology is applied to a demonstrative case, showing how reduced barrier performance lead to significant increase of frequency of more severe final scenarios, with a consequent reduction of the likelihood of less critical outcomes.

References

- Antonioni G., Landucci G., Necci A., Gheorghiu D., Cozzani V., 2015 Quantitative assessment of risk due to NaTech scenarios caused by floods, *Reliability Engineering and System Safety*, 142, 334-345.
- CCPS, 2001, Layer of protection analysis: simplified process risk assessment, AIChE Centre of Chemical Process Safety, New York, NY.
- Cozzani V., Antonioni G., Landucci G., Tugnoli A., Bonvicini S., Spadoni G., 2014, Quantitative assessment of domino and NaTech scenarios in complex industrial areas, *J. Loss Prev. Proc. Industries*, 28, 10-22.
- CSB, 2018, Organic peroxide decomposition, release and fire at Arkema Crosby following Hurricane Harvey flooding, US Chemical Safety and Hazard Investigation Board, Washington DC.
- Delvosalle C., Fiévez C., Pipart A., Debray B., 2006, ARAMIS Project: A comprehensive methodology for the identification of reference accident scenarios in process industries, *Journal of Hazardous Materials*, 130, 200-2019.
- Girgin S., 2011, The Natech events during the 17 August 1999 Koaceli earthquake: aftermath and lessons learned, *Natural Hazards and Earth System Sciences*, 11, 1129-1140.
- Karagiannis G.M., Chondrogiannis S., Krausmann E., Turksezer Z.I., 2017, Power grid recovery after natural hazard impact, EUR 28844 EN, European Commission, Luxembourg.
- Krausmann E., Cruz A.M., Salzano E., 2017, Natech Risk Assessment and Management, *Reducing the Risk of Natural-Hazard Impact on Hazardous Installations*, Elsevier, Amsterdam, NL.
- Labib A., Harris M.J., 2015, Learning how to learn from failures: The Fukushima nuclear disaster, *Engineering Failure Analysis*, 47, 117-128.
- Landucci G., Argenti F., Spadoni G., Cozzani V., 2016, Domino effect frequency assessment: The role of safety barriers, *Journal of Loss Prevention in the Process Industries*, 44, 706-717.
- Landucci G., Argenti F., Tugnoli A., Cozzani V., 2015, Quantitative assessment of safety barrier performance in the prevention of domino scenarios triggered by fire, *Reliability Engineering and System Safety*, 143, 30-43.
- Landucci G., Gubinelli G., Antonioni G., Cozzani V., 2009, The assessment of the damage probability of storage tanks in domino events triggered by fire, *Accident Analysis and Prevention*, 41, 1206-1215.
- Landucci G., Necci A., Antonioni G., Argenti F., Cozzani V., 2017, Risk assessment of mitigated domino scenarios in process facilities, *Reliability Engineering and System Safety*, 160, 37-53.
- Mannan S., 2005, *Lee's Loss Prevention in the Process Industries*, 3rd edition, Elsevier Butterworth-Heinemann, Oxford, UK.
- Misuri A., Casson Moreno V., Quddus N., Cozzani V., 2019a, Lessons learnt from the impact of hurricane Harvey on the chemical and process industry, *Reliability Engineering and System Safety*, 190, 106521.
- Misuri A., Landucci G., Cozzani V., 2020, Assessment of safety barrier performance in Natech scenarios, *Reliability Engineering and Systems Safety*, 193, 106597.
- Misuri A., Landucci G., Vivarelli S., Bonvicini S., Cozzani V., 2019b, Risk-based Vulnerability Analysis of Chemical Facilities Affected by Flooding, *Chemical Engineering Transactions*, 77, 523-528.
- Sklet S., 2006, Safety barriers: definition, classification, and performance, *Journal of Loss Prevention in the Process Industries*, 19, 494-506.
- PSA, 2013, Principles for barrier management in the petroleum industry, Petroleum Safety Authority, Stavanger, Norway.