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# Assessment of safety barrier performance in the mitigation of domino scenarios caused by Natech events

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*Alessio MISURI[1], Gabriele LANDUCCI[2], Valerio COZZANI[1,*]*

[1]LISES – Department of Civil, Chemical, Environmental and Materials Engineering, Alma Mater Studiorum – University of Bologna, via Terracini 28, 40131, Bologna, Italy

[2]Department of Civil and Industrial Engineering, University of Pisa, Largo Lucio Lazzarino 2, 56126, Pisa, Italy.

**Corresponding author: valerio.cozzani@unibo.it*

## Abstract

Technological accidents triggered by natural hazards (Natech accidents) are likely to escalate in cascading scenarios with severe consequences. Indeed, safety barriers implemented in process plants to prevent and mitigate accidents may be affected by natural hazards as well. The present study proposes a novel comprehensive method to assess safety barriers and protection systems performance modification during natural hazards, as well as the resulting modification in the expected frequency of secondary technological scenarios that may arise. In particular, the probability and frequency of domino scenarios initiated by Natech events are assessed considering the possible concurrent degradation of safety barrier performance in case of floods and earthquakes. An approach based on layer of protection analysis is adopted to quantify safety barrier performance degradation, accounting for the modification of barrier availability and effectiveness. A dedicated event tree analysis is applied to domino effect assessment and quantification of overall escalation scenarios. The results obtained allowed a detailed assessment of the expected frequency of secondary mitigated escalation scenarios, considering the possible effect of barriers degradation within Natech events.

**Keywords**

Natech; domino effect; escalation; safety barriers; mitigation.

## 1. Introduction

The hazard related to the impact of natural disasters on installations where relevant quantities of hazardous substances are stored and processed, as the chemical and process industry, the Oil & Gas industry, the nuclear industry and some sectors of the manufacturing industry, has become a matter of growing concern in the last decades [1–3]. Severe conjoint threats may develop from the interaction between natural hazards and such critical infrastructures, due to the relevant inventories of hazardous substances handled and processed in these facilities [4,5]. Among the technical literature, technological accidents triggered by natural hazards are usually termed as Natech accidents [6–8]. Previous studies estimated that about 5% of industrial accidents reported in databases have been caused by natural hazards [9,10]. Nevertheless, the number of disasters is partly growing possibly due to climate change [11–14], thus these figures may be expected to grow consequently in the foreseeable future.

The consequences of Natech events may be extremely severe when compared to conventional technological accidents [15–17]. Indeed, multiple simultaneous failures may occur and the likelihood of accident propagation through domino effect is relevant also due to the potential impact of the natural event on safety systems [10,18]. For instance, during the Koaceli earthquake (1999) massive quantities of hazardous chemicals such as acrylonitrile and diesel fuel were released in the Izmit Bay area [19–21]. Moreover, multiple fire scenarios developed in a petroleum product storage park due to multiple simultaneous hydrocarbon releases, and fire was able to spread to nearby tanks since firefighting intervention was severely hampered due to concurrent damages to water pumping stations and pipelines [21].

Another critical aspect associated with Natech scenarios is related to the possible impact of the natural event on the safety systems and utilities, thus reducing the possibility of accident mitigation or even causing specific accident scenarios [22]. For instance, during Hurricane Harvey (2017), besides multiple oil spills from storage tanks, the prolonged power outage and the consequent loss of refrigeration of a peroxide storage led to chemical decomposition and fires [23,24].

In the literature, several methodologies to perform Quantitative Risk Assessment (QRA) of Natech scenarios are available and have been applied to test cases [25–27]. These methods rely on the adoption of equipment vulnerability models aimed at determining the failure probability of process equipment given the impact of different natural events [28], such as floods [29–33], earthquakes [34–36], lightning strikes [37,38] and wind [32]. However, these methodologies feature relevant limitations when considering the role of domino effect and safety barriers, which should be taken into account for a more realistic and comprehensive estimation of Natech risk. Moreover, despite established methodologies for the quantitative assessment of domino propagation are available in the literature [39–41], the case of escalation during Natech events is seldom considered [42,43].

Previous studies evidenced that the impact of natural events may affect the integrity and availability of safety barriers [23,24]. However, to the knowledge of the authors, no methods are available in the literature for the quantitative assessment of the effect of the degradation of safety barriers on system integrity and availability in Natech accident scenarios. Indeed, a number of studies focus on the role of safety barrier management, addressing both the general framework related to the protection and integrity of complex system (e.g. see [44]), and the specific context of domino effect assessment [45-48]. However, such approaches do not address the expected reduction of safety system performance due to natural hazards, preventing their direct application to the case of Natech accidents.

The present study is aimed at introducing an innovative methodology to include the concurrent safety barrier degradation due to the impact of the natural event in the probabilistic assessment of mitigated domino scenarios triggered by Natech events. The method relies on specific data obtained in a recent study, in which the performance modification of a set of relevant safety barriers during floods and earthquakes has been evaluated, based on expert elicitation [49]. The probabilistic framework in which safety barriers data are implemented is based on a Layer of Protection Analysis (LOPA) approach [50,51]. Probability and frequency of mitigated domino scenarios during natural hazards are evaluated through a tailored event tree analysis (ETA) [52–54]. An indicator-based approach is applied to perform a simplified evaluation and monitoring of the reduction of barrier performance in domino escalation mitigation/prevention [54].

The following parts of the paper are organized as follows. The methodology proposed for escalation characterization and frequency assessment of mitigated domino scenarios triggered by Natech accidents is described in Section 2. A case study is presented in Section 3 in order to demonstrate the applicability of the proposed framework. Section 4 is dedicated to the presentation of results and to the discussion on the main findings, and Section 5 reports the conclusions.

## 2. Methodology

### *2.1 Overview*

Figure 1 outlines the methodology developed in the present study. With respect to previous methodologies, on the one hand, the proposed procedure allows the evaluation of the probability and frequency of mitigated domino scenarios caused by natural events, considering the possible concurrent depletion of safety barriers. On the other hand, the methodology provides a specific and original approach to the quantitative assessment of the performance of the safety barriers in Natech event, by the calculation of the probability of failure on demand and of the effectiveness of barrier action in the specific conditions occurring during Natech scenarios (steps 5 and 6 in Figure 1).

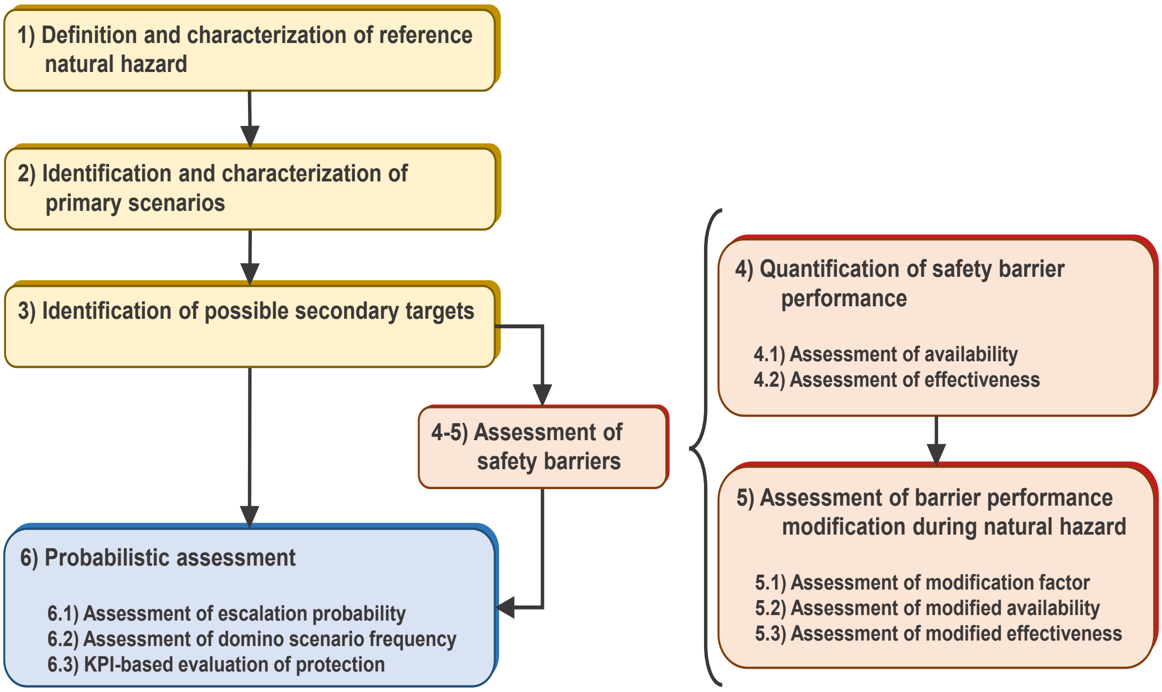


*Figure 1: Methodology proposed for frequency assessment of mitigated domino scenarios and for the assessment of safety barrier performance in the mitigation of escalation of Natech events (KPI: Key Performance Indicators).*

Step 1 (see Figure 1) is aimed at defining the reference natural hazards that may affect the industrial site under analysis and at performing a characterization of its main features, with a degree of detail suitable for industrial risk assessment studies. The natural hazard should be defined in terms of time of return, which may be easily related to a frequency of occurrence, and of magnitude of impact at the site of concern. The present study focuses on earthquakes and floods, since these events were responsible for the most severe Natech events reported in industrial accident databases, as highlighted in the dedicated literature [18], but may be extended to other categories of natural hazards.

In the specific framework of Natech, the severity of floods may be characterized in terms of floodwater height and velocity, while the magnitude of earthquakes is usually assessed estimating the values of the horizontal component of peak ground acceleration (PGA) [25,28,55]. This approach leads to the selection of a limited number of reference scenarios for the natural events, each characterized by a time of return and an intensity, representing the natural hazard present on the site [25,28,56].

Coherently with the state of the art of Natech assessment, the expected time of return and the effects of the natural hazards are considered independent (that is, the assessment considers either the effect of a flood or that of an earthquake, and does not consider any correlation among them or their potential effects). Moreover, barrier degradation due to the effect of previous natural events is not considered (that is, safety barriers are assumed to have undergone a regular maintenance).

Primary scenarios caused by Natech are then identified and characterized in terms of frequency and consequences (Step 2 in Figure 1). The identification of primary events is carried out adopting specific methodologies developed for the framework of Natech scenarios, described in detail elsewhere [17,56]. The frequency of primary loss of containment (LOC) events can be calculated multiplying the expected frequency of the natural event of concern by the conditional probability of equipment damage, obtained applying equipment vulnerability models [29,30,36], as exemplified in Appendix A.

Specific event trees may be used to define the possible primary scenarios following the LOC events [17,56] and to identify the relevant escalation vectors. Indeed, previous studies [10,17] highlighted that most of Natech events reported in databases collecting data on industrial accidents involved the LOC of petrochemical products [23,57], which may lead to fire scenarios.

The possible domino targets may then be identified (Step 3 in Figure 1) through the application of threshold-based approaches available in the literature [58–60]. These methods are based on the comparison between the actual value of the physical effects impacting on equipment items (e.g., heat radiation in case of stationary fires, or peak overpressure in case of explosions) and threshold values below which escalation is considered not credible.

For each identified target, it is then necessary to consider the possible escalation likelihood modification due to the presence of safety barriers for accident prevention and mitigation (Steps 4 and 5 in Figure 1). However, these systems may be impacted as well by the natural hazard [49], thus a specific evaluation of their performance modification is required (Step 5 in Figure 1). Details on the quantification of barrier performance and on its modification due to the concurrent natural events are discussed respectively in Sections 2.2 and 2.3.

The assessment of the frequencies of the overall escalation scenarios may then be carried out (Step 6 in Figure 1). Probit models based on equipment time to failure (*TTF*) when exposed to heat load may be applied to assess the probability of escalation due to domino effect triggered by fire [28,61,62] (Step 6.1 in Figure 1). Dedicated methodologies to account for safety barriers are then applied to perform mitigated domino scenario probability and escalation frequency assessment [52–54] (Step 6.2 in Figure 1). These two steps are discussed in Section 2.4. Finally, a performance analysis of safety barriers and protection systems is carried out through a specific indicator-based methodology (Step 6.3 in Figure 1), which is presented in Section 2.5.

### 2.2 *Quantitative performance assessment of safety barriers*

Safety barriers are hereby defined as physical and non-physical measures intended to prevent, mitigate or control dangerous deviations of the industrial system under analysis or accidents [63–65]. Several frameworks for the classification of safety barriers are available in the literature [66–69]. In the following, the classification is based on the barrier working principle [50,70]. This allows classifying safety barriers as:

- passive barriers: physical protection systems not requiring activation to perform their function, such as fireproofing or containment dikes [71];
- active barriers: requiring external activation, such as water deluge systems (WDS) and sprinklers [72–75];

- procedural barriers: procedures and contingency plans performed by internal personnel or external teams to face the occurrence of major accidents (e.g., intervention of firefighters).

Not every barrier has the same performance in serving the intended safety function, as the performance may be influenced by several parameters, including reliability, effectiveness and robustness [76]. As the performance of safety barriers is a critical aspect in evaluating the probability of accident scenarios caused by Natech events, its characterization is needed to support the probabilistic assessment of final scenarios.

A number of methodologies are available in the literature for barrier performance characterization, which have been developed in various fields of application of safety barrier conceptualization and require a variety of input information [50,66,67,70]. In the present study, a tailored LOPA approach developed for the assessment of mitigated escalation scenarios is adopted [52] (Steps 4.1 and 4.2 in Figure 1). The approach estimates the safety barriers performance introducing: i) a probability of failure on demand (PFD), that is, the probability that the system is unavailable when its safety function is required; and ii) the barrier effectiveness ($\eta$), that is the probability that the barrier is successful in performing escalation prevention conditioned to its successful activation.

The value of the barrier PFD is related to the system architecture and to the reliability of its components, and may be assessed with standard reliability techniques, such as fault tree analysis, in case sufficient data on components can be retrieved in the technical literature. On the other hand, in case of lack of data, a PFD may still be estimated through the application of simplified risk-based approaches [77,78]. A comprehensive catalogue of reliability data sources is reported elsewhere [79].

The effectiveness parameter $\eta$, being a direct expression of the quality of a barrier function, should be estimated considering the specificity of the system, as well as other performance influencing factors (e.g. system installation, maintenance, quality of operations management, etc.) [52–54].

More details on the application of the concepts of PFD and $\eta$ in the assessment of mitigated domino escalation are reported elsewhere [52–54].

### *2.3 Assessment of barrier performance modification in Natech events*

Once the original performance of safety barriers is quantified, baseline values of PFD and $\eta$ are modified taking into account the effect of the natural event (Step 5 in Figure 1), adopting the methodology and the dataset developed by Misuri et al. [49]. Performance modification factors $\phi$ were elicited from experts through a covariate approach [80,81], and implemented for the assessment of the safety barriers (Step 5.1 in Figure 1). The 2nd quartile of failure probability distributions obtained was selected as the value of $\phi$ in order to minimize the effect of the outliers [49]. Performance modification factor $\phi$ can be interpreted as the likelihood that barrier systems are impaired or damaged by natural hazards, hence higher values (i.e., close to 1) indicate a higher probability that the barrier will fail in providing a successful protection action.

A subset of relevant safety barriers along with the specific modification factors in case of flood ($\phi_f$) and earthquake ($\phi_e$) is reported in Table 1. In the same table, the uncertainty on the elicited parameters is expressed as the interval comprised between the 1st and the 3rd quartiles (indicated as Q1 and Q3, respectively) of the distributions obtained.

*Table 1: Performance modification factors for safety barriers in case of floods ($\phi_f$) and earthquakes ($\phi_e$). $Q_1$=1st quartile of distribution; $Q_3$=3rd quartile of distribution. Data gathered from* [49].

| **Safety barrier** | $\phi_f$ | $[Q_1, Q_3]_f$ | $\phi_e$ | $[Q_1, Q_3]_e$ |
|---|---|---|---|---|
| Inert-gas blanketing system | 0.5 | [0.25, 0.75] | 0.625 | [0.5, 0.85] |
| Automatic rim-seal fire extinguishers | 0.15 | [0.15, 0.25] | 0.5 | [0.25, 0.75] |
| Fixed / Semi-fixed foam systems | 0.375 | [0.25,0.50] | 0.5 | [0.5, 0.75] |
| WDS / Water Curtains / Sprinklers | 0.375 | [0.18, 0.75] | 0.75 | [0.5, 0.85] |
| Hydrants | 0.5 | [0.25, 0.75] | 0.5 | [0.25, 0.75] |
| Fire activated valves | 0.5 | [0.25, 0.50] | 0.375 | [0.25, 0.69] |
| Fire and gas detectors | 0.5 | [0.25, 0.75] | 0.5 | [0.25, 0.75] |
| Shut down valves | 0.25 | [0.15, 0.50] | 0.5 | [0.25, 0.50] |
| Blow down valves | 0.25 | [0.15, 0.50] | 0.25 | [0.15, 0.50] |
| Fire walls | 0.2 | [0.15, 0.25] | 0.5 | [0.25, 0.75] |
| Blast walls | 0.15 | [0.15, 0.75] | 0.25 | [0.25, 0.50] |
| Fireproofing | 0.15 | [0.15, 0.25] | 0.25 | [0.15, 0.44] |

The proposed framework, based on the implementation of the modification factors, thus tailoring baseline barrier performance, derives from considerations and lessons learned from past Natech accidents [10,19,23] (Steps 5.2 and 5.3 in Figure 1). In particular, in the case of active barriers it is assumed that the effect of the natural hazard induces the increment of the PFD of active barriers (i.e., reducing their availability), with a negligible effect on effectiveness after successful activation. In case of passive barriers, the effectiveness is the sole parameter to be reduced by the impact of the natural event, since in this case the barrier does not need any specific activation or action to provide its effect (i.e., failure on demand to provide the protective action is not applicable to this barrier category).

Thus, by the proposed approach, a single modification factor obtained from expert elicitation is applied either to modify the PFD (in the case of active barriers) or the effectiveness (in the case of passive barriers).

Given these premises, while in the case of procedural barriers a specific analysis is always needed to assess the expected performance, a general approach may be applied to assess the degradation of barrier performance in the case of active and passive barriers.

In the case of active barriers, the performance parameters of the $i$-th active barrier are modified according to Eqs. (1)-(2):

$$PFD_{j,i} = 1 + \left(\phi_{j,i} - 1\right)\left(1 - PFD_{0,i}\right) \tag{1}$$

$$\eta_{j,i} = \eta_{0,i} \tag{2}$$

where $\phi_{j,i} \in [0,1]$ is the performance modification factor for $j$-th reference natural hazard scenario, and $PFD_{0,i}$ and $\eta_{0,i}$ are the baseline values for the probability of failure on demand and effectiveness, respectively. As discussed above, the impact of natural hazards on the effectiveness of active barriers is neglected, thus the effectiveness value is considered equal to the baseline value, $\eta_{0,i}$. In the case of barriers not specifically designed to resist to natural events, it is possible that $PFD_{0,i}$ is much lower that $\phi_{j,i}$ (that is: failure in case of natural events is significantly higher than conventional failure probability), but a specific assessment is always needed.

With respect to passive barriers, since the barriers are always available and do not need any activation to provide their action, the modification of the performance of the $i$-th passive barrier may be quantified considering only the effectiveness, as in Eq. (3):

$$\eta_{j,i} = \left(1 - \phi_{j,i}\right) \eta_{0,i} \tag{3}$$

where $\phi_{j,i} \in [0,1]$ is the performance modification factor of the *j*-th reference natural hazard scenario, and $\eta_{0,i}$ is the baseline effectiveness value, as shown in Section 2.2.

In the case of procedural barriers, modification factors are not available in the literature, thus a general approach to assess performance degradation during Natech events, as that proposed for active and passive barriers, is not possible. Specific approaches, depending on the procedure foreseen, should be developed. An example is provided for the specific case of a procedural barrier consisting in the emergency response following a fire, aimed at preventing escalation. The characterization of effectiveness is based on a specific approach obtained adapting that originally developed by Landucci et al. [54] to Natech scenarios. In the original approach, the effectiveness $\eta$ is evaluated based on the comparison of the time the equipment is expected to withstand the received heat load, the *TTF,* and the typical time required for the final mitigation of the scenario (*TFM*, time for final mitigation) [54]. However, the *TFM* obtained by the original methodology, not accounting for the specific conditions that may arise during a Natech scenario, may be considered as a "best-case" value. In order to obtain a worst-case estimation of possible delays due to the complex environmental conditions that may be faced during compound disasters as earthquakes and floods [82], *TFM* was modified applying a methodology accounting for delays in response due to harsh environmental conditions. More details on the evaluation of PFD and $\eta$ for emergency response to fires are reported in Appendix B.

### *2.4 Quantification of domino escalation frequencies*

The first part of the frequency assessment consists in estimating the frequency of primary LOCs induced by the natural event (as part of Step 2 in Figure 1). If a frequency of the reference natural hazard scenario, $f_{nh}$, is estimated starting from the time of return, it is possible to calculate the frequency of the primary LOC events $f_{I,LOC}$ (where the subscript I,LOC indicates a primary LOC scenario) for an equipment item as:

$$f_{I,LOC} = f_{nh} \cdot P_{nhd} \tag{4}$$

where $P_{nhd}$ is the equipment damage probability to the impact of the reference natural hazard scenario. The $P_{nhd}$ damage probability can be estimated using equipment vulnerability models or observational fragility curves available in the literature [29,30,36].

The description of the vulnerability models applied in the present study is reported in Appendix A.

Primary Natech scenarios are identified through dedicated methodologies [17,25,56,83] and the evaluation of physical effects is performed through conventional integral models for consequence assessment [71,84–86]. Subsequently, a tailored ETA is applied to include the effect of safety barriers and their performance in escalation probability and frequency assessment. The methodology is based on the logical operators described as gates in Table 2, which are adapted from a previous study [54].

*Table 2: Definition of operators to be used in ETA. $f_{IN}$: gate input frequency, PFD: Probability of failure on demand, $\eta$: effectiveness parameter, $P_D$: equipment failure probability due to domino escalation. Adapted from* [54].

| Gate type | Representation and quantification | Description |
|---|---|---|
| a | $f_{IN}$ → a: $Out_1 = f_{IN} * [PFD + (1-\eta) * (1-PFD)]$; $Out_2 = f_{IN} * (1-PFD) * \eta$ | Simple composite probability gate (type "a"): unavailability, expressed as probability of failure on demand, is combined with a single probability value for the effectiveness. |
| b | $f_{IN}$ → b: $Out_1 = f_{IN} * [PFD + (1-\eta) * (1-PFD)]$; $Out_2 = f_{IN} * (1-PFD) * \eta$ | Composite probability distribution gate (type "b"): unavailability, expressed as probability of failure on demand, is combined with a probability distribution expressing the effectiveness. It is possible to use an integrated effectiveness value, obtaining the quantification rule reported. |
| c | $f_{IN}$ → c: $Out_1 = f_{IN} * PFD$; $Out_2 = f_{IN} * (1-PFD) * (1-\eta)$; $Out_3 = f_{IN} * (1-PFD) * \eta$ | Discrete probability distribution gate (type "c"): depending on barrier effectiveness, three or more events may originate |
| d | $f_{IN}$ → d: $Out_1 = f_{IN} * P_D$; $Out_2 = f_{IN} * (1-P_D)$ | Vessel fragility gate (type "d"): based on the status of the target equipment (e.g., received heat load, status of protections), the failure probability is calculated through equipment vulnerability models. |

As shown in the table, the uppermost branch $Out_1$ of each gate represents the failure of the barrier in mitigating escalation. For gates "a" and "b", $Out_2$ represents the case of successful mitigation. In the specific case of gate "d", which is a target vessel fragility gate rather than a gate expressing barrier performance, $Out_1$ represents the mechanical failure of the target, while $Out_2$ indicates that the target withstands heat radiation. The probability of failure due to domino propagation $P_D$ to be implemented in gate "d" is identified through the application of probit models based on equipment *TTF* [61]. Gate "c" instead has been specifically designed to assess emergency response performance in escalation prevention [52,54]. Thus, $Out_2$ represents the case of mitigated domino scenarios due to the successful activation of emergency response, but with a $TFM$ higher than $TTF$. On the contrary, $Out_3$ is the case of successful mitigation due to successful response and $TFM$ lower than $TTF$.

*2.5 Quantification and monitoring of barrier degradation*

A set of indicators was applied to carry out a simplified quantitative evaluation and monitoring of barrier performance degradation in preventing/mitigating domino effects (Step 6.3 in Figure 1). This set of indicators has been developed for passive and active barriers in previous studies on mitigated domino escalation assessment [54]. In particular, two Key Performance Indicators (KPIs), namely A and B, are associated to each hardware barrier. The A KPI is defined as:

$$A = \frac{\sigma}{Out_1/f_{IN}} \quad (5)$$

where $\sigma$ is a reference PFD indicating a high performance in reduction of escalation probability, $f_{IN}$ is the input frequency to the barrier gate operator and $Out_1$ is the output frequency of mitigation failure. Therefore, the ratio $Out_1/f_{IN}$ is the probability of barrier failure (either due to lack of activation or ineffectiveness once activated), which is associated with the uppermost branch of each gate presented in Table 2. The A KPI thus summarizes the overall probabilistic performance of each barrier compared to a required safety level. The application of the risk-based methodology defined in IEC61508 and IEC61511 standards [77,78] evidenced that a safety function with Safety Integrity Level (SIL) 3 is required for domino escalation prevention [54]. According to the SIL definition, a safety function with SIL3 has a failure probability on demand between $10^{-4}$ and $10^{-3}$, thus the latter the value was conservatively assumed for parameter $\sigma$ in the case-study.

The B KPI is defined as:

$$B = \frac{TTF - TTF_u}{TFM - TTF_u} \quad (6)$$

where $TTF$ and $TTF_u$ are the values of the time to failure of the equipment item considered respectively in presence and in the absence of the barrier, while $TFM$ is the time required for final mitigation of the fire, which is highly site specific and may be estimated according to the simplified methodology presented in a previous study [52]. The B KPI, thus, specifically quantifies the increase in $TTF$ achieved through the implementation of fire protection barriers (e.g. WDS, etc.), with respect to the time required for emergency intervention at site.

## 3. Case-study

A reference case study was defined to assess the modification of risk figures caused by barrier performance degradation during Natech events. The layout considered is shown in Figure 2. The layout is composed of two atmospheric tanks storing liquid flammable materials (T1, T2) and of a pressurized vessel storing LPG (P1). The main features of the equipment items are summarized in Table 3.

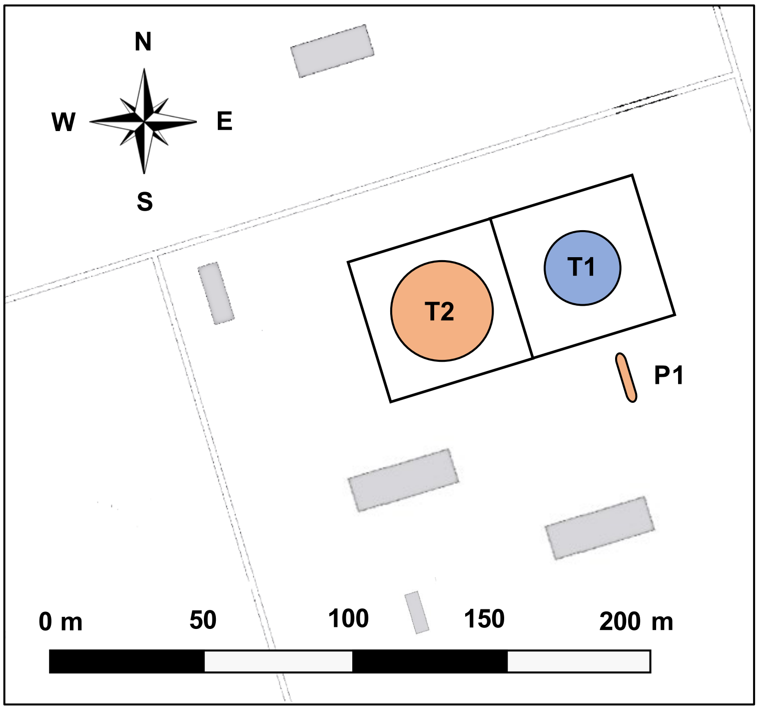


*Figure 2: Layout considered for the case study.*

*Table 3: Equipment items considered in the case-study. Tank T1 was considered the source of the LOC causing the primary Natech scenario.*

| ID | Type | Capacity [$m^3$] | Diameter [m] | Length/Height [m] | Substance | Inventory [ton] |
|---|---|---|---|---|---|---|
| *T1* | *Atmospheric tank* | *5000* | *24.4* | *10.8* | *Gasoline* | *3000* |
| T2 | Atmospheric tank | 4300 | 32 | 5.4 | Crude oil | 3000 |
| P1 | Pressurized vessel | 105 | 2.6 | 20 | LPG | 52 |

The facility was assumed to be located in a natural hazard prone area, and to be exposed to the risk of severe floods and earthquakes. The reference natural hazards are described in Table 4. As shown in the table, the flood with a time of return of 500 years was assumed as the reference scenario for flood hazards. The flood scenario with this return time is the more severe flood scenario usually considered in flood hazard analysis [25,29,30]. In the case of earthquakes, the event with 10% exceedance probability in 50 years is assumed as reference case, which roughly corresponds to a 500 years return time, that, for the sake of simplicity, was assumed as the reference value of return time in the analysis of the case-study [18]. Thus, the frequency of both the natural hazards assumed in the case-study results of $2.0\times10^{-3}$ $y^{-1}$, allowing a straightforward comparison of the results obtained for the two different natural hazards.

*Table 4: Reference scenarios selected for flood and earthquake in the case study, and consequent LOC and primary scenario probabilities calculated for tank T1 in Table 3. Ignition probability of 0.9 is assumed.*

| ID | Description | Features of the natural event | Return time $t_r$ [y] | Frequency $f_{nh}$ [$y^{-1}$] | Damage probability of T1 $P_d$ | Frequency of primary LOC from T1 $f$ [$y^{-1}$] | Frequency of primary pool fire $f_{PF}$ [$y^{-1}$] |
|---|---|---|---|---|---|---|---|
| W1 | High depth flood | $h_w = 2.0\ m$ $v_w = 0.5 \frac{m}{s}$ | 500 | 2.00E-03 | 2.40E-01 | 4.79E-04 | 4.31E-04 |
| E1 | Severe earthquake | $PGA = 0.5\ g$ | 500 | 2.00E-03 | 1.74E-01 | 3.47E-04 | 3.13E-04 |

Since the aim of the present study is to assess the probability and frequency modification of escalation scenarios due to barrier degradation rather than to perform a complete QRA, for the sake of simplicity a single primary event due to Natech is considered in the analysis of the case-study.

The primary Natech scenario is assumed to only involve the atmospheric tank T1, while T2 and P1 are possible targets for domino effect escalation. The target tanks T2 and P1 are equipped with the safety barriers reported in Table 5. Both tanks are protected with pressure safety valves (PSV), while tank T2 is equipped with foam-water sprinklers, and P1 with water deluge system (WDS) and high rating passive fire protection material (PFP). Emergency response plan to a fire involving tank T1 foresees the intervention of emergency teams to further protect both items by fire monitors.

It should be remarked that the methodology developed allows considering also all the other primary Natech scenarios generated by tanks T2 and P1 and the following domino effects. This was not done only in order to simplify the case-study and for the sake of brevity.

*Table 5: Safety barriers considered in the case study. Subscription legend: o= original value; f= in case of flood; e= in case of earthquake. The "X" marks indicate the equipment items for which each safety barrier is considered.*

| Barrier | Gate | $PFD_0$ | $\eta_0$ | $PFD_f$ | $PFD_e$ | $\eta_f$ | $\eta_e$ | T2 | P1 |
|---|---|---|---|---|---|---|---|---|---|
| Foam-water sprinkler system | b | 5.32E-03 | 0.954 | 3.78E-01 | 5.03E-01 | 0.954 | 0.954 | X | |
| WDS | a | 4.33E-02 | 1 | 4.02E-01 | 7.61E-01 | 1 | 1 | | X |
| PFP | a | 0 | 0.999 | 0 | 0 | 0.849 | 0.749 | | X |
| PSV | a | 1.00E-02 | 1.00 | 1.00E-02 | 1.00E-02 | 1.00 | 1 | X | X |
| Emergency teams | c | 1.00E-01 | 0;1 | 1.00E-01 | 1.00E-01 | 0;1 | 0;1 | X | X |

Table 5 shows the original PFD and effectiveness of each barrier, which have been retrieved from literature sources [52,71,79,87,88], and the modified values calculated according to Eqs(1)-(3), applying the values of $\phi_f$ and $\phi_e$ reported in Table 1. The choice of the appropriate gate for each barrier is made according to the specific features of the barrier, the consequence of barrier failure and the specific functionality of the barrier, which determines how the barrier effectiveness is expressed to model the quality of barrier function (i.e., as single probability value, or as continuous or discrete probability distribution). For the case of WDS, PFP and PSV, gate "a" has been selected since their effectiveness can be expressed as a single value. For the specific case of foam-water sprinkler systems, gate "b" was selected. This choice is made since sprinkler performance is generally expressed as the probability distribution of fire extinguishment in technical literature [52]. Nevertheless, for the sake of simplicity, the minimum value retrieved in the literature is conservatively adopted in this study to assess foam-water sprinkler effectiveness. For the case of emergency intervention, gate "c" has been selected to include partial success in mitigation, as explained in Section 2.4. Further details on gate selection and specific examples are reported in a previous study to which the reader is referred for further details [42].

The frequencies of the primary Natech scenarios are assessed adopting fragility models available in the literature (see Section 2.4 and details in Appendix A). In the case of floods (W1), the vulnerability model developed in [29], considering buckling as the failure mechanism, has been applied, while in case of earthquake (E1), the tank is conservatively assumed unanchored and the vulnerability is assessed by the fragility models reported in [36]. It should be remarked that any alternative appropriate equipment damage model among those available in the literature could be used for the assessment.

A LOC causing the complete release of the tank content in 10 minutes is conservatively assumed [25,55]. An ignition probability of 0.9 is assumed both in the case of earthquake and of flood. This choice is in agreement with previous studies, and it is deemed appropriate to highlight the high likelihood of ignition in case of high magnitude compound disasters as earthquakes and floods [25,55,56]. Thus, both for flood and for earthquake, the reference primary Natech scenario is a pool fire involving the total inventory of tank T1.

Three possible endpoint scenarios were considered as possible consequences of the primary event, taking into account escalation due to domino effect and the safety barriers considered, involving either tank T2 or P1:

- unmitigated domino scenarios, developing from the escalation of the primary scenario in the absence of activation or with the lack of effectiveness of safety barriers;
- mitigated domino scenarios, that is, scenarios with potentially reduced consequences due to partial activation or reduced effectiveness of safety barriers in the accident sequence;
- no domino scenarios, in which the escalation is avoided due to activation and effective response of the safety barriers.

The consequence assessment of the primary pool fire was carried out using integral models [71,85,86]. For the sake of simplicity, a single value of ambient temperature, wind velocity and atmospheric stability class were considered: 10°C, 2m/s and F. The calculated maximum incident heat radiation on the surface of each considered target is $60 kW/m^2$.

The $TTF$ of targets and the probability of failure as a function of the heat load caused by the primary Natech scenario is evaluated by the approach suggested by [61]. Best-case $TFM$ values of 65 and 90 min were obtained for P1 and T2 by the simplified approach, based on the features of the fire scenario and on the vessel geometries suggested by [52], not considering the specific conditions of Natech scenarios. A worst-case $TFM$ value of 400 min was also estimated, considering the harsh conditions of emergency response in Natech events (see Appendix B).

For the sake of comparison, domino effect causing escalation from a pool fire originated by the internal failure of Tank T1 is also considered. A LOC causing the release of the entire inventory of tank T1 in 10 minutes was assumed. A frequency of $2.5\times10^{-6}$ $y^{-1}$ was estimated for the pool fire following the LOC, based on values suggested in the literature for LOC and immediate ignition [54,84]. Due to the assumptions introduced, the same heat radiation values calculated for the primary Natech scenarios are associated with this pool fire. In the absence of a natural hazards acting on the site, the baseline values for PDF and effectiveness of the safety barriers reported in Table 5 were assumed in the analysis.

## 4. Results and discussion

### *4.1 Assessment of probabilities and frequencies of escalation scenarios*

The methodology described in Section 2 has been applied to the case study. The set of event trees developed to analyse the case study is reported in Appendix C. Since in the case-study, for the sake of simplicity, the consequences of a single primary event were considered in all the three cases of domino effect analysed (due to internal causes, due to flood or due to earthquake), it is possible to directly compare the probabilities of escalation given the primary event.

Figure 3 shows the results obtained for the conditional probability of the three end-point scenarios considered in the analysis (unmitigated domino scenarios, mitigated domino scenarios and no domino scenario) calculated considering the possible impact of the natural event on the safety barriers. The figure also reports the expected overall frequencies of these final scenarios, considering the frequency estimated for the primary event triggering the domino sequence, either in the presence or in the absence of natural events. Conditional probabilities and frequencies of domino scenarios in case of absence of hardware mitigation (thus without add-on active and passive barriers) and only accounting for generic data for internal emergency intervention, by the method proposed by Landucci et al. [61]) are also included in Figure 3 as reference values for the sake of comparison.

As shown in the figure, the conditional probability associated with unmitigated scenarios exhibits a significant increase due to the impact of flood or earthquake on the barriers considered. For pressurized vessel P1, this increment is of about three orders of magnitude, while in case of tank T2 it is of about five times the original value. Thus, the degradation of barrier performance seems to have a greater impact on pressurized vessels rather than on atmospheric tanks. However, atmospheric storage tanks are inherently more vulnerable to domino escalation caused by fire (as shown by the values of probability of unmitigated escalation reported in Figure 3), due to their lower mechanical resistance. Thus, the probability of unmitigated escalation scenarios affecting T2 is still significantly higher than the value for P1, even considering barrier performance degradation.

It is also worth noting that the effect of barrier performance degradation is different for earthquakes and floods, depending on the different effects that such events may have on the degradation of barrier functions, in accordance with previous findings [49].

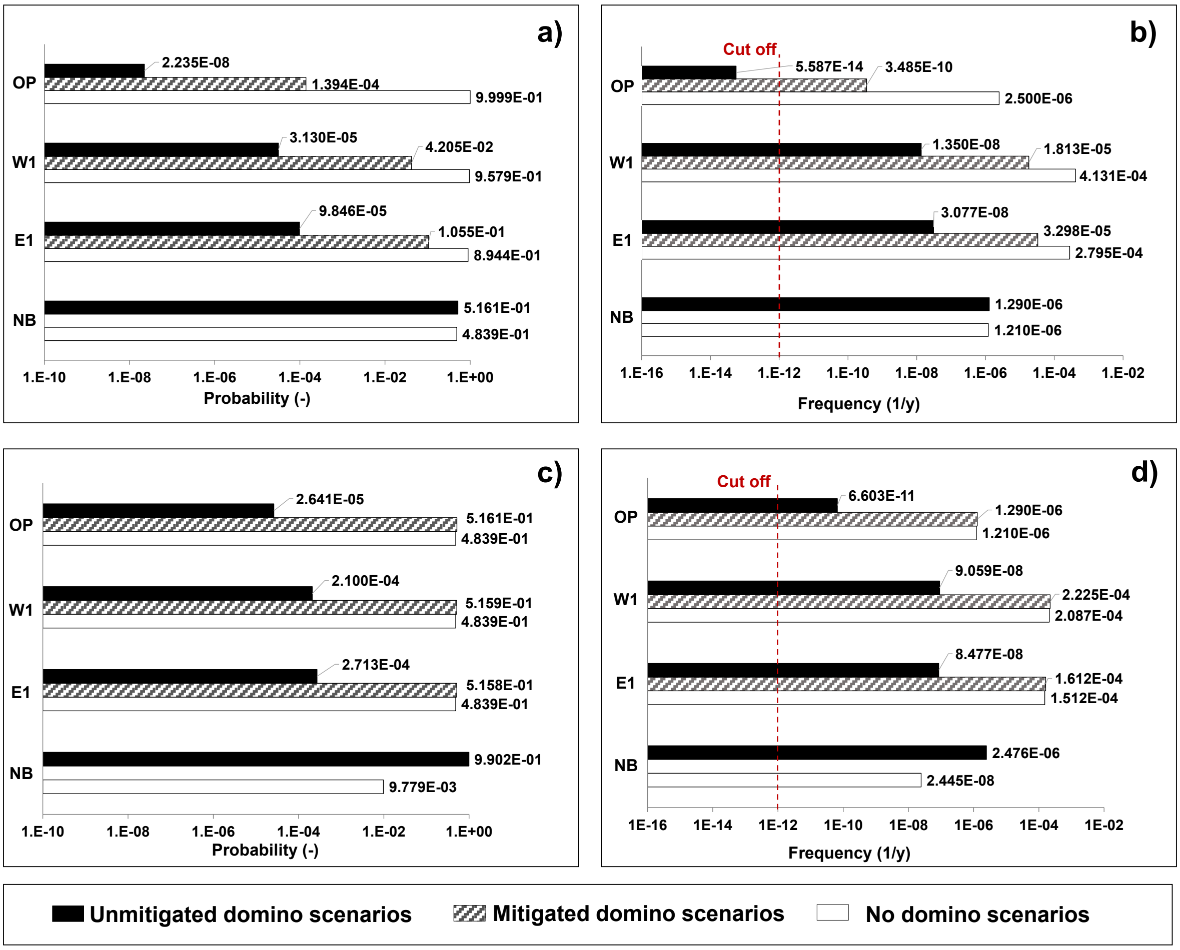


*Figure 3: Conditional probabilities and overall frequencies of the end-point domino scenarios considered for tanks P1 and T2 following a primary Natech event affecting tank T1, calculated without considering hardware barriers and only generic internal emergency interventions. (a) Conditional probabilities of end-point scenarios calculated for tank P1; (b) Overall frequencies of end-point scenarios calculated for tank P1 considering the frequency of the primary event estimated for tank T1; (c) Conditional probabilities of end-point scenarios calculated for tank T2; (d) Overall frequencies of end-point scenarios calculated for tank T2 considering the frequency of the primary event estimated for tank T1. OP: original performance, i.e. domino effect considered only as a consequence of internal failures and baseline values assumed for safety barrier performance; W1: flood-induced primary Natech scenario; E1: earthquake-induced primary Natech scenario.*

The overall frequencies of escalation scenarios given primary Natech events are shown in Figure 3-b and Figure 3-d. The figures also report a baseline cut-off value ($1.0\times10^{-12}$ $y^{-1}$) suggested in the literature [54]. As a general remark, it can be observed that the frequencies of unmitigated escalation scenarios triggered by Natech events are at least three orders of magnitude higher than those of unmitigated escalation from conventional primary scenarios due to internal causes. Actually, all escalation scenarios arising from Natech primary scenarios feature higher frequency values compared to those triggered by conventional internal failures. This is a direct consequence both of the higher frequency of natural hazards compared to the frequency of random internal failures (even in case of events having a high time of return, as those considered in the case study), and of the effect of the degradation of safety barriers when impacted by natural events.

As shown in Figure 3-b, in the case of vessel P1 the frequency of unmitigated scenarios is negligible in the absence of Natech scenarios. Considering the Natech scenarios and the simultaneous barrier degradation, the frequency of unmitigated scenarios increases of about five orders of magnitude, well above the suggested cut-off value. In Figure 3-d a similar trend is present. However, the frequency of unmitigated escalation scenarios is limited but may not be neglected, according to the cut-off criteria selected, also in the case of domino effect due to scenarios caused by internal failures, since the heat load on tank T2 is high and atmospheric tank resistance is lower than that of pressurized vessels.

Thus, starting from the data and assumptions introduced in the case-study, the results obtained show that Natech-induced scenarios have frequencies far higher than conventional escalation scenarios. Even if such results should be considered specific for the case-study analysed and derives from the specific assumptions introduced, still some general conclusions may be drawn. In particular, the case-study evidences that the escalation of Natech scenarios may have an important role in determining the risk figures of a site.

### *4.2 KPI-based assessment of barrier performance degradation*

The approach described in Section 2.5 was applied to monitor the modification of barrier performance during Natech events. The set of KPIs was calculated both considering baseline barrier performance and the modified performance due to W1 and E1 reference

Natech scenarios. Results are shown in the chart reported in Figure 4, which is divided into three parts:

- "green area": a region in which both indexes A and B are equal or higher than the reference value of 1. This is the optimal protection region, in which the barrier performance provides an optimal risk reduction;
- "yellow area": intermediate region, in which at least one of the two indexes is below the reference value;
- "red area": region in which both indexes are lower than 1, indicating poor risk reduction.

Grey markers show the baseline performance of the barriers considered, while blue markers and orange markers show the performance during W1 and E1, respectively. The performance of barriers aimed at increasing the $TTF$ of targets (i.e., WDS and PFP) is represented together with the area of uncertainty on the value (i.e., area covered by pattern in Figure 4). The uncertainty on KPI A is expressed calculating the index considering the 1st and the 3rd quartiles of $\phi$ distributions (see Table 1), while KPI B is calculated both considering original $TFM$ (best case) and a modified $TFM$ based on the methodology for harsh environment described in Appendix B [82] (worst case). For the barriers not significantly providing a direct effect on the $TTF$ of the target (i.e., foam system and PSV), a constant minimum value for the B index was set to $10^{-3}$. For the foam system, only the uncertainty on KPI A is available. The values of the KPIs are calculated with the same method described above and are represented with whiskers. Both during W1 and E1, in the best case the PFP falls in the yellow-shadowed area of the KPI plot. However, considering the worst case (i.e., a severely hampered emergency intervention) PFP falls in red-shadowed area of the plot, indicating that both KPI values are below the reference levels for high protection. PSV is the only barrier that is not affected either by W1 or by E1 in accordance with the outcome of a previous study [49], as PSV failure was never reported in available data on Natech scenarios.

It is also worth noting that PFP has the best performance in hampering escalation in domino scenarios from internal failures. However, in case of natural hazards, the performance of PFP in preventing escalation from Natech events is reduced, falling into the red area. Figure 4 also shows that in the case-study considered the earthquake E1 affects safety systems more severely than flood W1, as it clearly emerges from the more pronounced shift toward lower values of the A index.

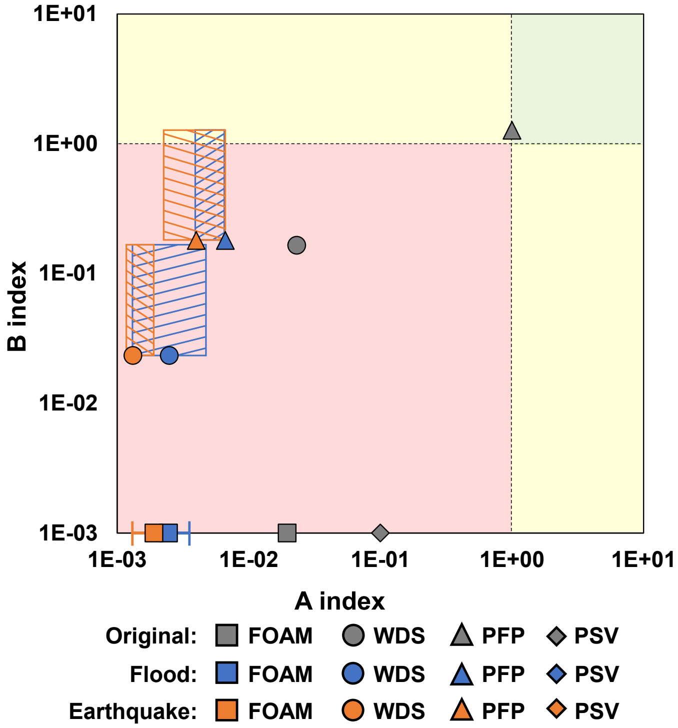


*Figure 4: Comparison between original and degraded barrier performance as shown by KPI values, A and B, as defined by Eqs.(5) and (6) respectively. Legend: FOAM = Foam-water sprinkler system, PSV = Pressure safety valve, WDS = Water deluge system, PFP = Passive fire protection. Blue-dashed area = Uncertainty for flood W1, orange-dashed area = Uncertainty for earthquake E1. Uncertainty region for the foam-water sprinkler system is indicated by whiskers.*

### *4.3 Discussion*

The results obtained highlight the modification of expected conditional probabilities and overall frequencies of escalation scenarios when considering also primary scenarios induced by Natech events, as in the case of earthquakes and floods affecting a chemical or process facility. The method developed provides some key figures needed to develop a comprehensive Quantitative Risk Assessment (QRA) procedure accounting for Natech events and for the possible domino effects triggered by such scenarios, also considering the action of safety barriers and their degradation during Natech events. As shown in Figure 3, both the high expected frequency of Natech primary scenarios in areas exposed to natural hazards [29] and the critical degradation of barrier availability and effectiveness during Natech events [49] were proven to lead to frequencies of both mitigated and unmitigated escalation scenarios that may be orders of magnitude higher than those corresponding to escalation scenarios from conventional internal failures.

Even if by no way the numerical results of the case-study should be generalized, since the expected frequency of natural events and of Natech accidents may change dramatically depending on the geographical location of the site and on its exposure to natural hazards, still the significance of the escalation scenarios induced by primary Natech is clearly shown by the results obtained.

It should also be noted that, despite the case-study illustrated addresses the context of chemical and process industry, the safety barrier conceptualization is employed in a variety of industrial sectors [63,89,90]. Thus, the approach proposed can be applied to a broad number of industrial systems, also considering that several activities beside those of the chemical and process industry involve the bulk storage and processing of relevant quantities of hazardous substances: Oil & Gas, mining, industrial ports, nuclear, etc. For instance, in the in nuclear industry, where there is a clear evidence of the potential severity of accidents caused by natural events [91], system safety is traditionally based on the defence-in-depth concept [92–94]. Several studies aim at a more robust safety assessment of these installations, also widening and consolidating the use of probabilistic safety assessment (PSA) in this framework [95,96], and specific solutions are proposed to improve the resilience of these installations to natural events (e.g. see [97]). The specific approach proposed in the present framework is suitable for application within a "defence in depth" approach, and may contribute to provide a more realistic assessment of the performance of the protection layers when affected by natural events as floods and earthquakes. Indeed, being PSA a reportedly important mean for improving the understanding of system vulnerabilities, as well as a pivotal tool to enhance defence-in-depth principle implementation [91,98], the inclusion within the PSA framework of explicit performance modification of layers of defence during natural hazard might drive better risk-informed decision-making for accident prevention and mitigation.

A further remark concerns the potential importance of the approach in the framework of Safety Integrity Level (SIL) Assessment [99,100]. The use of SIL Assessment to determine and verify the safety performance of safety barriers and protection systems, with particular reference to safety instrumented systems, is a common practice in several industrial sectors, such as the Oil&Gas, chemical, nuclear and space industry [101]. The quantitative approach developed in the present study may be easily complemented with the performance assessment of Safety Instrumented Functions (as several active barriers may be considered), which is needed both in the SIL determination phase based on LOPA

[99,101,102], and in the SIL verification phase [99,100-102]. Moreover, the outcomes of the present study may be implemented in specific studies dealing with the physical degradation of safety instrumented systems [103], thus supporting the performance analysis of depleted safety barriers.

As a final remark, it should be considered that the present study only addressed the expected frequency of escalation scenarios induced by Natech events. In perspective, also the severity of final escalation scenarios should be assessed, enabling the quantification of overall risk figure modifications due to the contribution of barrier degradation in Natech events.

## 5. Conclusions

A methodology to include the impact of natural hazards on safety barriers in the quantification of the probability and frequency of escalation scenarios caused by domino effect was developed. Specific performance modification factors were implemented and applied to domino effects triggered by Natech primary scenarios. The results highlight that the impact of natural hazard on safety barriers leads to a significant increase in the probability and frequency of unmitigated domino scenarios. As confirmed by the assessment of specific KPIs, safety barrier performance may be significantly depleted during Natech events. In addition, the approach developed may support risk-based decision making addressing the integration of safety barriers and of specific protections aimed at reducing the potential severity of Natech events. Indeed, the results of the case study show that the safety barriers addressing the prevention and mitigation of domino effect from conventional scenario may not be effective to prevent domino effect from Natech primary scenarios. The development of specific standards to assess the performance of safety barriers during the impact of natural events may contribute to a more effective control of risk due to Natech events and to enhance the resilience of chemical and process plants to the impact of natural hazards.

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## Appendix A

This appendix shows the equipment vulnerability models for assessing conditional failure probability $P_{nhd}$ given the reference flood W1 and earthquake E1.

*Table A. 1: Vulnerability model for atmospheric tanks during floods* [29]*, with description of relevant input parameters and their assumed value for the application to the case study presented in Section 3.*

| ***Vulnerability model equations*** | | |
|---|---|---|
| **Variable** | **Definition** | **Equation** |
| $CFL$ | Critical Filling Level | $CFL = \left( \frac{\rho_w k_w}{2} v_w^2 + \rho_w g h_w - P_{cr} \right) \Big/ \rho_f g H$ |
| $P_{cr}$ | Vessel critical pressure evaluated with the proposed simplified correlation | $P_{cr} = J_1 C + J_2$ in which<br>$J_1$ = -0.199<br>$J_2$ = 6950 |
| $P_{nhd}$ | Vessel vulnerability due to flooding | $P_{nhd} = \frac{CFL - \phi_{min}}{\phi_{max} - \phi_{min}}$ |
| ***Input parameters*** | | |
| **Item** | **Definition** | **Value adopted in Section 3** |
| $C$ | Vessel capacity | 5000 $m^3$ |
| $v_w$ | Flood water speed | 0.5 m/s |
| $h_w$ | Flood water depth | 2.0 m |
| $\rho_w$ | Flood water density | 1100 $kg/m^3$ |
| $\rho_f$ | Stored liquid density | 800 $kg/m^3$ |
| $k_w$ | Hydrodynamic coefficient | 1.8 |
| $H$ | Vessel height | 10.8 m |
| $g$ | Gravity acceleration | 9.81 $m/s^2$ |
| $\phi_{min}$ | Minimum operative filling level | 0.01 |
| $\phi_{max}$ | Maximum operative filling level | 0.75 |

For the case of flood W1, the vulnerability model for atmospheric storage tanks developed by Landucci et al. [29] is adopted. The model is based on the evaluation of the mechanical integrity of the containment under the action of floodwater. In particular, the resulting force excerpted by the flood on the item are composed by a static component due to water depth and a dynamic component linked to water kinetic energy. The vulnerability of the vessel can be determined as function of the liquid level below which the failure due to instability may happen. This parameter is named critical filling level ($CFL$) and can be estimated together with the vessel $P_{nhd}$ through the simplified correlation proposed in Table A. 1, together with relevant input parameters and their assumed value in this study.

For the case of earthquake E1, the vulnerability model for atmospheric storage tanks developed by Salzano et al. [36] is adopted. Fragility models are developed for different severities in terms of LOC, defined as risk states (RS). In this work, the model for RS=3, that is, the most severe release scenario corresponding to a release of the entire inventory in less than 10 min is conservatively applied. Moreover, the tank T1 is conservatively assumed unanchored, as said in Section 3. The model can be summarized in the form reported in Table A. 2.

*Table A. 2: Vulnerability model for atmospheric storage tanks during earthquakes adopted in the present study* [36].

| ***Vulnerability model equations*** | | |
|---|---|---|
| **Variable** | **Definition** | **Equation** |
| $P_{nhd}$ | Vessel vulnerability to earthquake | $P_{nhd} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y(PGA)-5} \left( exp\left[-\frac{u^2}{2}\right]\right) du$ |
| *Y(PGA)* | Probit variable as function of PGA [m/s²] (Unanchored, RS=3) | $Y(PGA) = -0.83 + 1.25 \cdot \ln\left(10^2 \cdot {PGA}/{g}\right)$ |
| ***Input parameters*** | | |
| **Item** | **Definition** | **Value adopted in Section 3** |
| *PGA* | Horizontal Peak Ground Acceleration | 4.9 $m/s^2$ (0.5g) |

## Appendix B

This appendix is intended to provide further details on the calculation of *PFD* and of effectiveness, $\eta$, for the characterization of emergency interventions.

The *PFD* can be assessed equal to $1.0\times10^{-1}$, which corresponds to the probability associated with human error according to LOPA literature [50] and to recent studies addressing ETA for domino escalation [52–54]. The evaluation of the effectiveness, $\eta$, may be performed according to the comparison between *TTF* and *TFM* at site, as proposed in Landucci et al. [54]. In case the *TTF* is lower than *TFM*, the emergency intervention should be associated to $\eta = 0$; on the contrary, in case the *TFM* is lower than *TTF* (i.e., in case of accident mitigation is achieved before target equipment failure due to fire), emergency intervention will be effective, and thus $\eta = 1$.

The value of time scale for accident mitigation is site specific, and a preliminary estimate of *TFM* is required to assess $\eta$. A simplified methodology based on fire mitigation strategy and the relative amount of water rate required for mitigation is applied in this study [52], leading to the calculation *TFM* values of 65 and 90 min respectively for P1 and T2. Nevertheless, the methodology was not developed considering the possibility that the emergency intervention is hindered by the possible unfavourable environment resulting from the impact of the natural hazard. Thus, the above reported results should be considered as baseline best-case values.

In order to perform a preliminary evaluation of the possible delay on emergency intervention, an approach originally proposed for assessing *TFM* in harsh environment has been adopted [82]. The modified *TFM* for onshore sites may be calculated according to the following relation:

$$TFM = \sum_{j=1}^{5} \tau_j \tag{B.1}$$

where $\tau_j$ are characteristic times required to perform the main operations that are required by emergency response.

*Table B. 1: Characteristic times to perform main emergency response operations in onshore sites as function of Harsh Environment Score (HES). Adapted from* [82].

| **Time** | **Operation** | **Correlation** | **Max $\tau_i$ [min] (HES=1)** |
|---|---|---|---|
| $\tau_1$ | Time to alert: maximum time required to start the emergency operation, which is usually composed to the detection time and the time needed to alarm onsite personnel and offsite teams | $\log_{10}(\tau_1) = -0.301 \times (1 - HES) + 1.000$ | 10 |
| $\tau_2$ | Time needed by external emergency teams to turn-out and reach the site | If $HES < 0.8$:<br>$\log_{10}(\tau_2) = -0.301 \times (1 - HES) + 1.380$<br>If $HES \geq 0.8$:<br>$\tau_2 = 60$ | 60 |
| $\tau_3$ | Time needed by external emergency teams to deploy firefighting equipment | $\log_{10}(\tau_3) = -0.301 \times (1 - HES) + 1.146$ | 14 |
| $\tau_4$ | Time needed by external emergency teams to carry out extra set-up operations | $\log_{10}(\tau_4) = -0.301 \times (1 - HES) + 1.204$ | 16 |
| $\tau_5$ | Additional time required in case one of more water transport system or interregional assistance are needed | If $HES < 0.8$:<br>$\log_{10}(\tau_5) = -0.301 \times (1 - HES) + 2.079$<br>If $HES \geq 0.8$:<br>$\tau_5 = 300$ | 300 |

The values of $\tau_j$ can be evaluated through correlations dependent on the Harsh Environment Score (HES), a parameter between 0 and 1 expressing the harshness of environmental conditions (0: normal conditions; 1: extremely harsh conditions). Conservatively, in the present study, a value of HES equal to 1 was assumed, as a worst-case scenario. Description of each operation considered, together with the correlation for estimating the characteristic times for onshore sites, and the resulting value assumed in this study are presented in Table B.1. With respect to the case-study considered, the worst-case value for *TFM* is assessed to be equal to 400 min for both P1 and T2.

## Appendix C

In the following, the event trees developed to analyse the case study are reported. In order to allow a better comparison of barrier performance, regardless the initial frequency of the primary scenario, a unitary frequency for primary event is assumed in Figures C.1 – C.4. The actual frequencies may thus be calculated multiplying by the actual initial frequency the numbers in the figures. As an example, the frequency of unmitigated escalation scenario from W1 involving P1 (coded as "FO_P1W1_01" in Figure C.1) considering barrier degradation, can be calculated as the product of $3.13\times10^{-05}$ (uppermost outcome in red from gate $d_1$ in Figure C.1) by $4.31\times10^{-04}$ $y^{-1}$ (frequency of pool fire from W1 according to Table 4), resulting in $1.35\times10^{-08}$ $y^{-1}$.

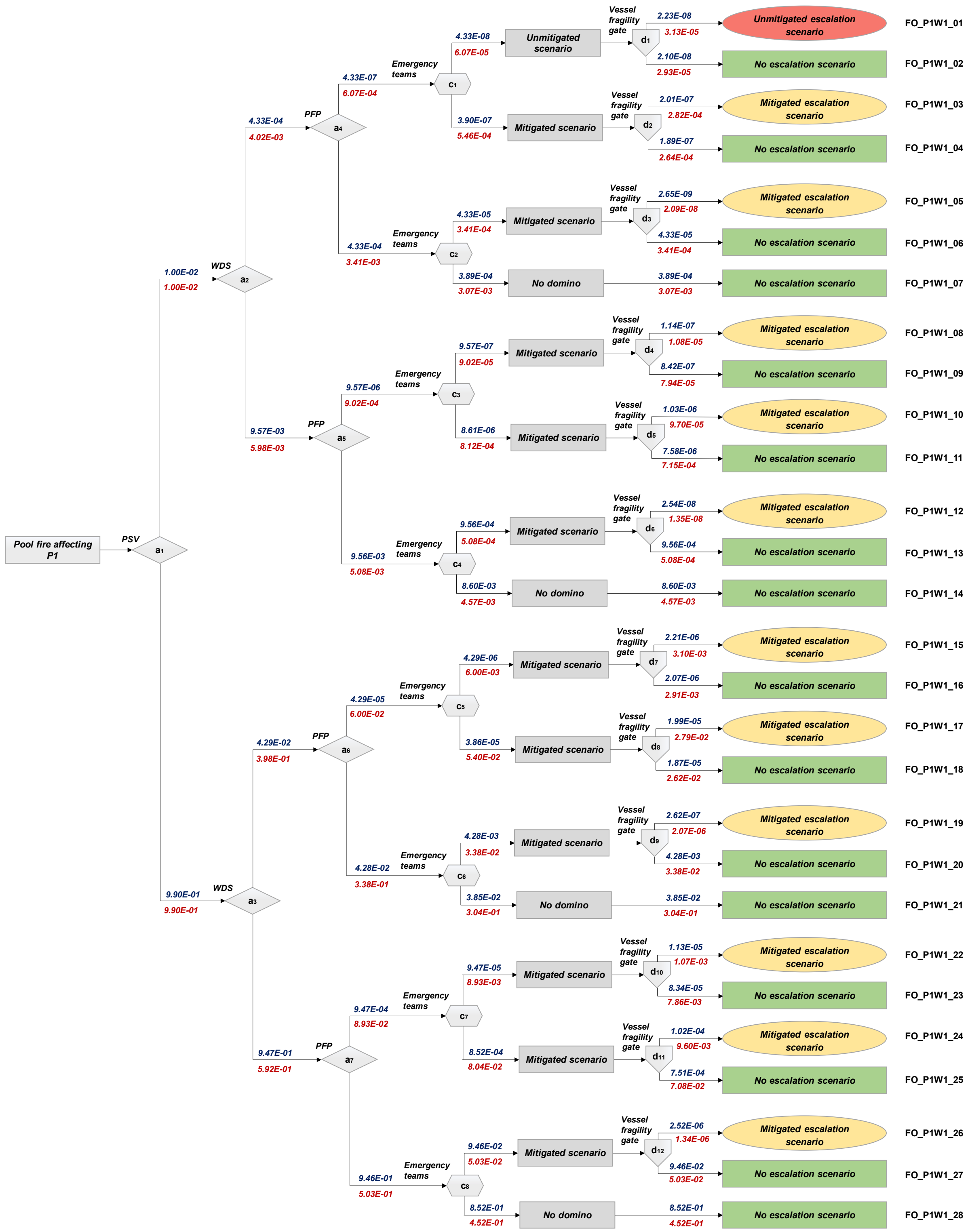


*Figure C. 1: Event tree analysis carried out for pressurized vessel P1, in case of W1 flooding conditions ($h_w = 2.0 m, v_w = 0.5 \frac{m}{s}$). The frequency of primary event is assumed unitary. Values in blue are calculated with original barrier performances, while values in red are obtained considering performance degradation.*

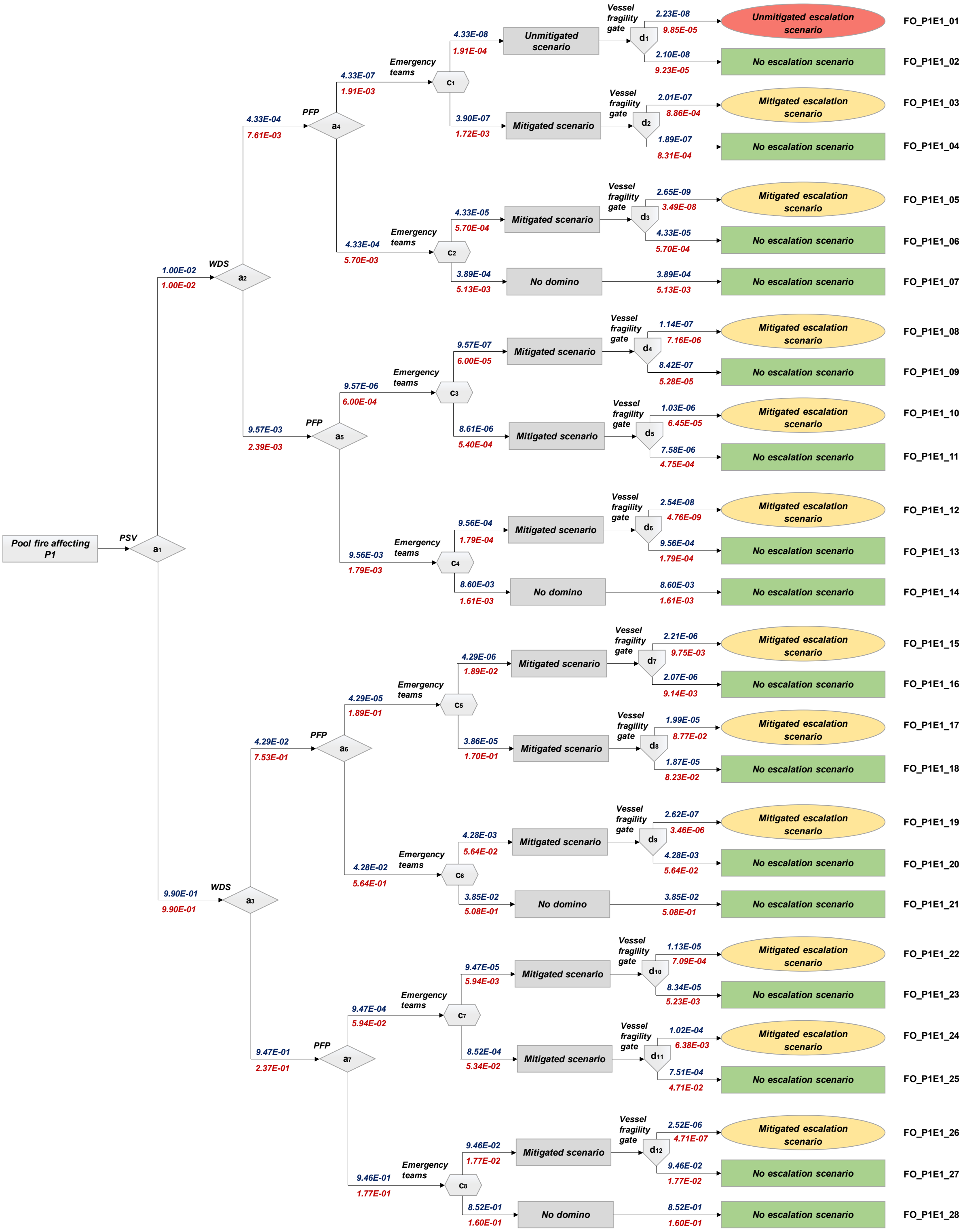


*Figure C. 2: Event tree analysis carried out for pressurized vessel P1, in case of E1 earthquake conditions (PGA = 0.5g). The frequency of primary event is assumed unitary. Values in blue are calculated with original barrier performances, while values in red are obtained considering performance degradation.*

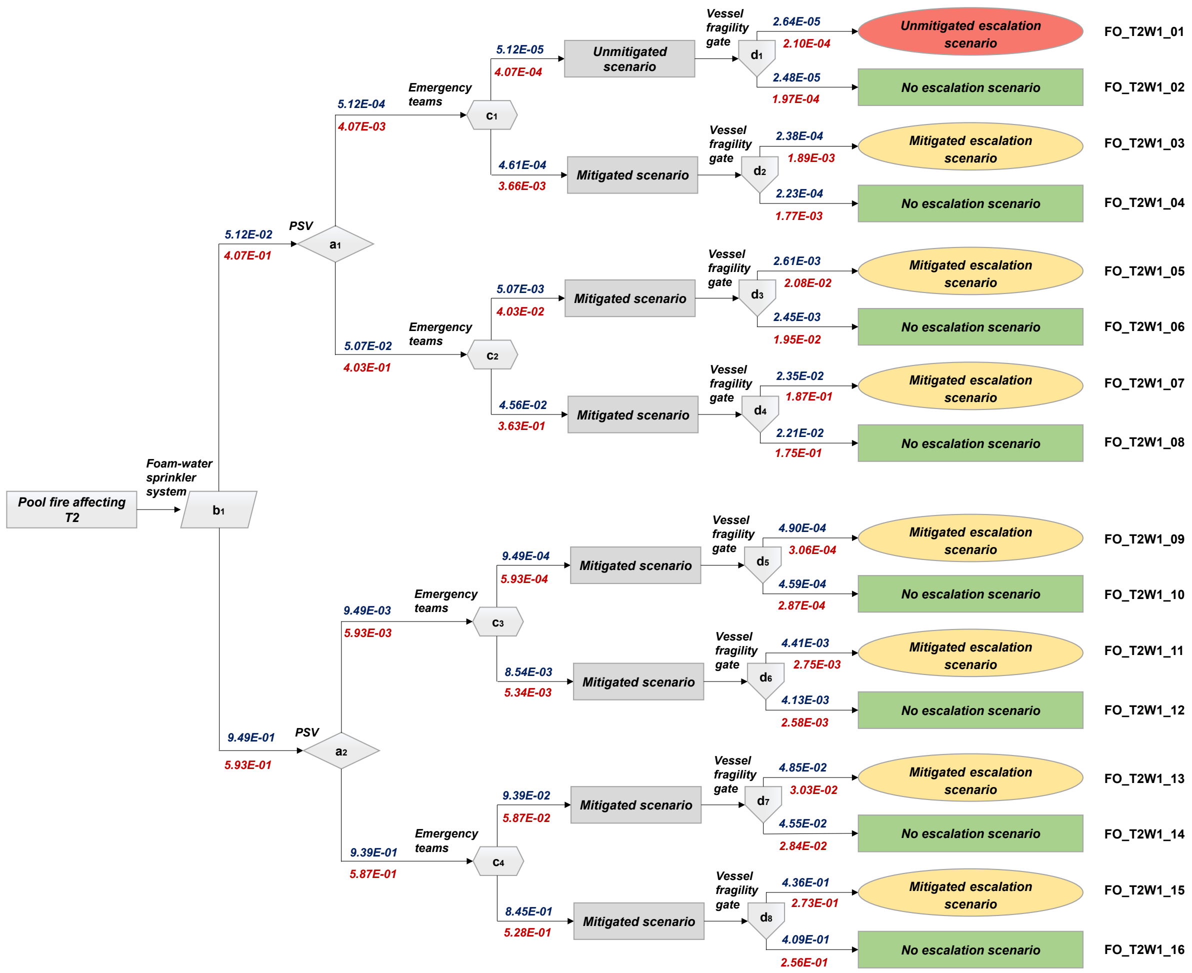


*Figure C. 3: Event tree analysis carried out for atmospheric tank T2, in case of W1 flooding conditions ($h_w = 2.0m, v_w = 0.5\frac{m}{s}$). The frequency of primary event is assumed unitary. Values in blue are calculated with original barrier performances, while values in red are obtained considering performance degradation.*

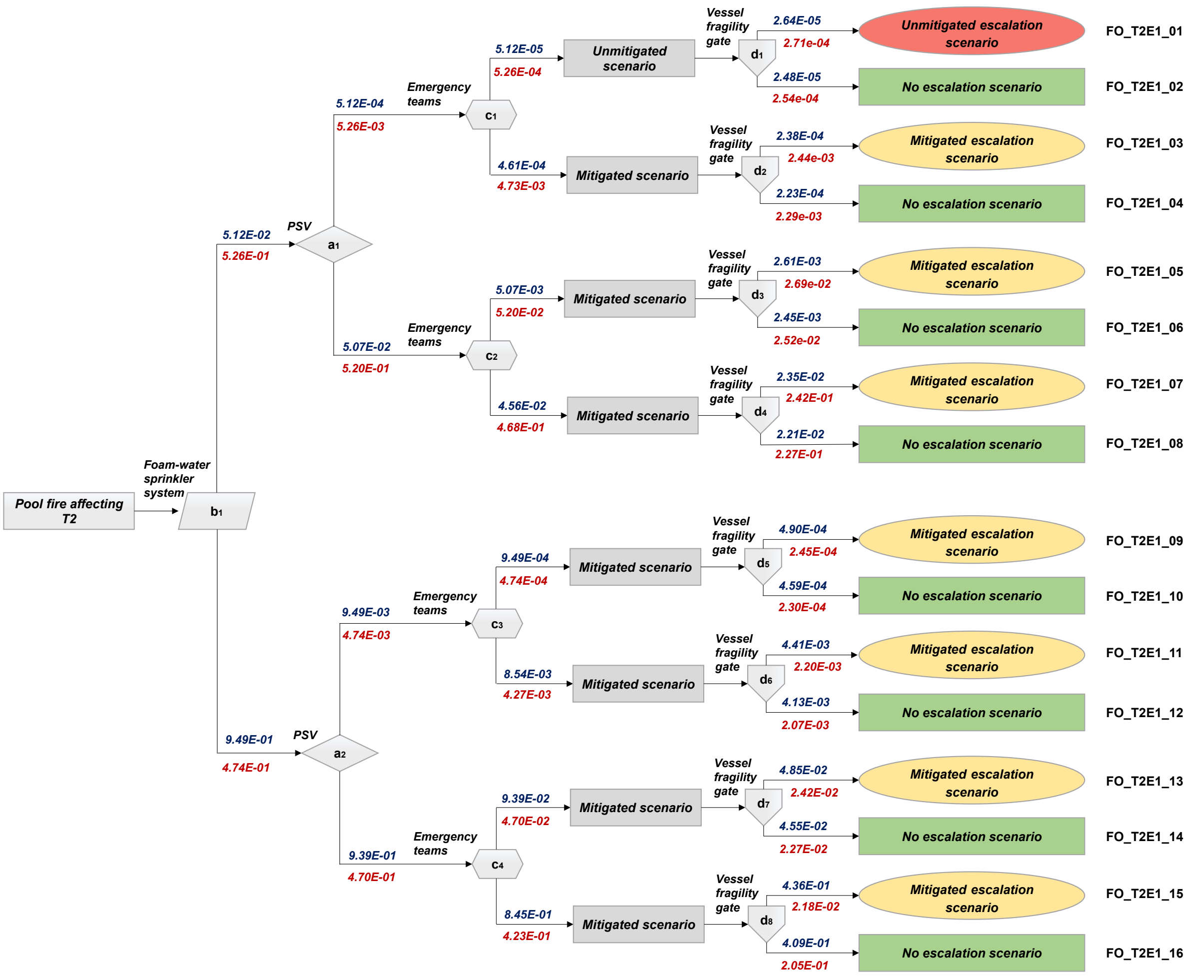


*Figure C. 4: Event tree analysis carried out for atmospheric tank T2, in case of E1 earthquake conditions (PGA=0.5g). The frequency of primary event is assumed unitary. Values in blue are calculated with original barrier performances, while values in red are obtained considering performance degradation.*

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