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Assessment of risk modification due to safety barrier performance degradation in Natech events

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Abstract

Natural hazards may cause severe technological accidents involving hazardous substances (Natech accidents). Along with process equipment also safety critical elements as safety barriers might be impacted by such events, thus reducing the protection provided and the possibility to prevent escalation and cascading effects. In the present study a comprehensive methodology is developed to address the quantitative assessment of the risk caused by the escalation of Natech accidents, specifically addressing the effect of the performance modification of safety barriers caused by the impact of the natural hazard. Barrier performance depletion is modelled through an innovative multi-level approach, and it is then introduced in the quantitative risk assessment procedure by a modified event tree analysis. A demonstrative application of the proposed methodology to a case study is provided, showing a relevant increase in risk figures deriving from the degradation of safety barrier performance caused by natural events. The proposed framework extends the systemic assessment of Natech scenarios to encompass the specific criticalities introduced by safety barrier performance modification induced by natural events, providing a more effective support to decision-making in the management and control of risk deriving from the interaction of natural hazards with technological installations.

Keywords

Natech; domino effect; escalation; safety barriers; quantitative risk assessment.

List of acronyms

EBD	Emergency Blowdown
EEI	External Emergency Intervention
ESD	Emergency Shutdown
ETA	Event Tree Analysis
EV	Expectation Value
FTA	Fault Tree Analysis
FWS	Foam-water system
LOC	Loss of Containment
LOPA	Layer of Protection Analysis
LSIR	Local Specific Individual Risk
MCS	Minimal Cut Set
PFD	Probability of Failure on Demand
PFP	Passive Fire Protection
PHM	Proportional Hazard Model
PLL	Potential Life Loss
PSA	Probabilistic Safety Analysis
PSV	Pressure Safety Valve
QRA	Quantitative Risk Assessment
SEP	Surface Emissive Power
WDS	Water Deluge System

1. Introduction

Managing the risk posed by technological accidents following of the impact of natural hazards on critical infrastructures has become a primary concern in the last decade, also due to the effect on climate change on the time of return of climate-related natural disasters [1]. The cascading events in which a sequence of technological scenarios involving the release of hazardous substances are triggered by the impact of a natural event as an earthquake or a flood are defined as Natech events [1], and may take place in any industrial facility where relevant quantities of chemicals are stored or processed, e.g. in the chemical and process sector, in oil&gas facilities and in other activities in the energy sector [2,3]. Indeed, recent natural disasters remarked the criticality of Natech accidents, highlighting both the vulnerability of technological installations to such events, and the potential severity of such scenarios [4]. For instance, the Tohoku earthquake and tsunami (2011) led to several Natech accidents involving chemical and petrochemical companies and to the tragic nuclear disaster at the Fukushima Dai-ichi nuclear power plant [5–7]. Also during Hurricane Harvey (2017) many industrial installations experienced damages that caused the release of hazardous substances, with severe consequences exacerbating the already critical damages brought by the tropical storm [8,9]. Many other examples of past accidents are available in the literature (see for instance [10,11]), demonstrating that Natech scenarios are complex and often involve the escalation of the primary technological scenarios. Past accidents also evidence that safety barriers in place for accident prevention and mitigation might be impacted as well. For instance, in several accidents safety systems dependent on lifelines (e.g. electric power) or auxiliary systems (e.g. compressed air, cooling water) have recurrently failed [9,12]. The structural damages and loss of integrity of physical barriers, such as catch basins and dikes (e.g., due to ground shaking during earthquakes, or water load during floods) is also documented [1,11].

Including these aspects in the assessment of Natech risk is not an easy task since not all the safety barriers may be degraded to the same extent and specific factors should be evaluated (e.g., barrier features, details on system architecture, etc.). Furthermore, the characteristics of the natural hazard itself might be critical in determining whether and to what extent these systems may be affected [13]. Whereas barrier performance depletion has been linked to a clear enhancement in the likelihood of accident escalation following primary technological scenarios in Natech events [14], to date no methodologies are available to quantify to what extent this performance shift impacts on risk figures. With the purpose of filling this gap, the present study proposes a comprehensive approach for the risk assessment of Natech accidents, integrating the quantitative assessment of the escalation from primary technological scenarios with a novel multi-level barrier assessment methodology. With respect to previous studies based on modification factors retrieved for generic barrier schemes [13], the multi-level approach proposed provides a significant advancement, allowing the assessment of barrier performance also considering system complexity into the analysis. Indeed, on the one hand, coarser approaches are suggested for the analysis of simpler systems. On the other hand, the application of more refined and information-intensive methods is proposed for more complex barriers, enabling the evaluation of case-specificities not accountable with generic barrier performance modification factors.

A concise state of the art is outlined in Section 2, evidencing the need to modify the current quantitative approaches for Natech quantitative assessment shifting the attention towards the role of safety barriers. The proposed methodology is presented in Section 3, with a specific focus on the steps aimed at safety barrier performance assessment. Then, in order to demonstrate methodology application and to provide an example of how risk figures related the escalation of primary scenarios in Natech events are modified considering updated barrier performance, a case study is defined in Section 4. Results and discussion are presented in Section 5, while Section 6 summarizes the main conclusions of the study.

2. State of the art

The quantitative assessment of the risk associated with Natech scenarios is a critical task. Most of the methodologies for Natech assessment proposed in the literature have been developed modifying conventional quantitative risk assessment (QRA) procedures to consider the possible multiple simultaneous releases that my be present in Natech events [15–17]. These methodologies allow the assessment of the risk related to primary technological scenarios from the release of hazardous substances triggered by equipment damage following the impact of reference natural events [18,19]. In the context of QRA, the equipment damage characterization, along with the quantification of the related probability, is performed applying simplified equipment vulnerability models which are available in the literature for a variety of natural hazards, such as earthquake [20–22], wind [23,24], flood [25–27], storm surge [28–30] and lightning strike [31,32]. Whereas the main body of research on Natech quantitative assessment methodologies is focused on these consolidated approaches derived from QRA, some recent publications investigated also the possibility of application of advanced tools for the frequency assessment of Natech scenarios. A relevant example of such research trend is the recent application of Bayesian networks to assess equipment vulnerability to floods [33,34] and to determine wildfire propagation in wildland-industrial interfaces, possibly leading to Natech accidents [35].

Most of the available methodologies do not consider the escalation of the primary technological events in Natech scenarios, and domino effect is seldom considered. Indeed, although some methodologies have been proposed to assess domino effects in conventional technological scenarios [36,37], both based on the extensions of QRA approaches [38–40] and on specific techniques as Bayesian networks [41–44], the possibility of escalation following primary technological scenarios in Natech events was considered only for specific natural hazards and/or for specific scenarios [45–47]. Moreover, to the knowledge of the authors, even in the few works addressing the assessment of domino effect in Natech events, the influence of safety barrier performance modification on overall risk figures was not specifically investigated to date [48], whereas it has been recently evidenced that the specific conditions occurring during natural events may impair or decrease their level of protection [13].

Whereas a number of studies focused on the role of safety systems and safety barriers, both addressing the general framework related to the integrity and protection of complex systems (e.g. see [49]), and the specific context of domino effect assessment [50–52], only few recent studies explored the issue of barrier performance assessment during or after the impact of natural events [13,14]. Indeed, despite it was demonstrated that the likelihood of escalation due to domino effect is significantly higher than expected when accounting for barrier degradation in Natech events [14], no specific method is available to date to consider the influence of such phenomenon from a risk assessment perspective.

3. Methodology

3.1 Quantitative assessment of Natech risk

In order to fill the gap evidenced in the analysis of the state of the art, a methodology was developed to assess the risk due to escalation triggered by domino effect in Natech scenarios, considering the role of safety barriers and their possible degradation. An overview of the method is provided in Figure 1.

As usual, in all the procedures aiming at the quantitative assessment of Natech risk, the starting point of the methodology is the definition and characterization of a reference set of natural hazards that will be considered in the analysis (Step 1 in Figure 1). Specific indications on the approaches to the quantitative characterization of natural hazards in terms of parameters expressing the frequency and the intensity of the events, with a degree of detail suitable for the assessment of Natech events, are available in the literature [19,53,54]. For instance, floods may be characterized in terms of time of return (linked to the frequency of occurrence) and floodwater depth and velocity [17,25,26]. Clearly enough, this step is not intended to provide a detailed characterization of natural hazards, but rather to have a concise expression of complex natural phenomena through a limited set of parameters, which is suitable for the framework of QRA [16]. A comprehensive discussion of how the reference events may be identified, on how the time of return of these events may be determined and on the related uncertainty is clearly out of scope of the present paper. Among the established methodologies available to accomplish this task, it is worth to mention the Probabilistic Seismic Hazard Analysis for earthquakes [55] or the use of hazard maps developed from data on past events for the case of floods [56]. Appropriate methodologies need to be selected with the contribution of sectorial experts, also considering the level of detail and the uncertainty compatible with the aims of the analysis. As an example, for the case of flood the accuracy of the estimates of scenario return time might be influenced by several factors as the amount of available data (and their related accuracy), the possible effects of climate change or modifications of river drainage area [57].

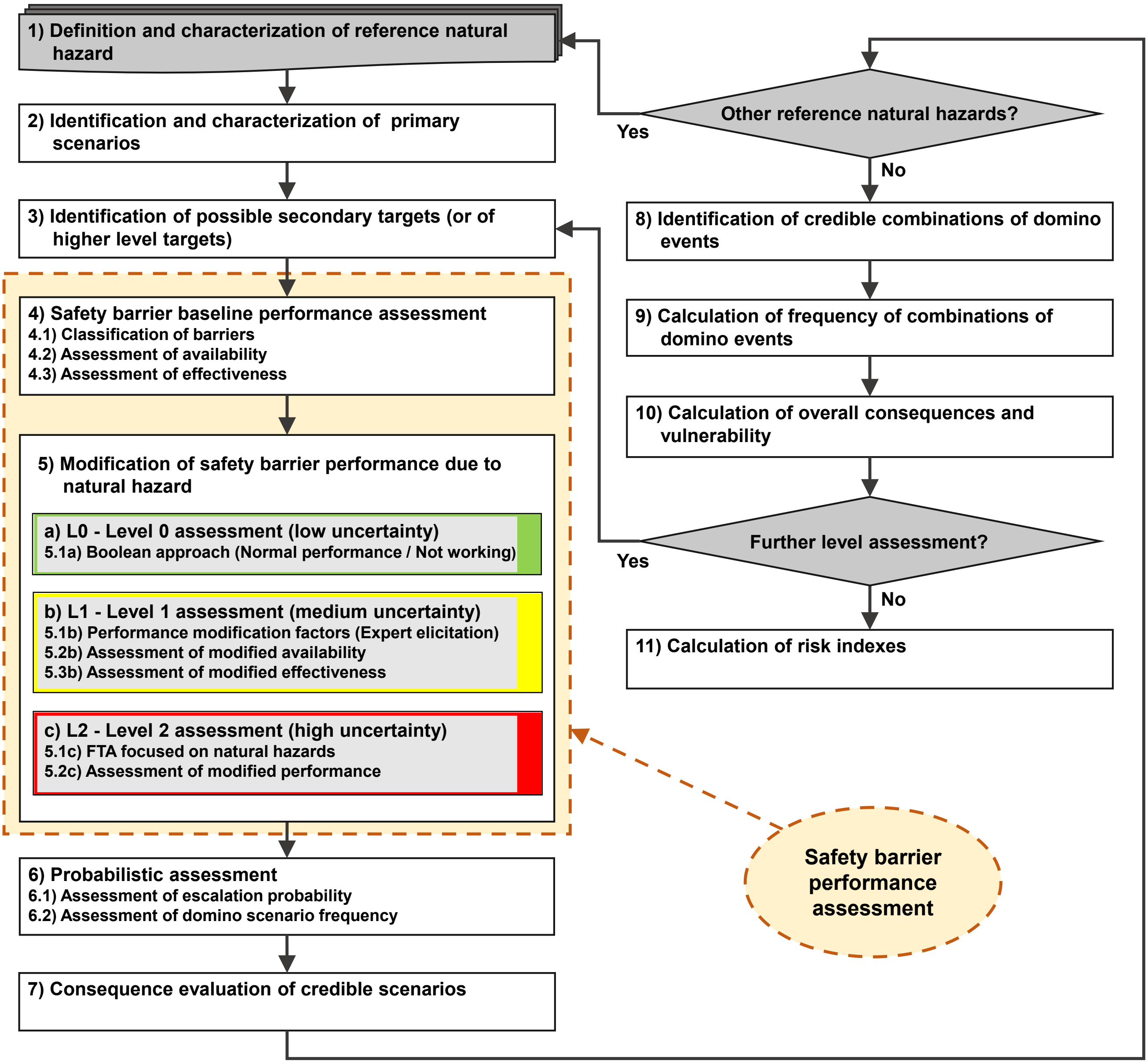

Figure 1: Flowchart for the methodology proposed for risk assessment of mitigated domino scenarios during natural events integrating the specific performance assessment of safety barriers considering the impact of the natural event.

The impact of the natural hazard on equipment items that may lead to the release of hazardous materials and, consequently, to primary technological scenarios is then assessed. Reference equipment items that may lead to a Loss of Containment (LOC) generating primary technological scenarios are identified (Step 2 in Figure 1). Specific criteria developed for the framework of Natech risk assessment for the identification and ranking of equipment to be considered, based on hazardous material inventory, substance features and storage conditions might be adopted (e.g., see [15,58]).

The frequency of primary LOC events $f_{I,LOC}$ can be assessed as follows [14]:

$$f_{I,LOC} = f_{nh} \times P_{nhd} \qquad (1)$$

where f_{nh} is the frequency of the reference natural hazard and P_{nhd} is the conditional probability of equipment failure, estimated applying equipment vulnerability models, as briefly mentioned in Section 2. Equipment vulnerability models are simplified empirical models allowing the assessment of the failure probability of an equipment item given the intensity of the natural event impacting on it [16]. A concise list of reference models has been collected in Section 2, while a more detailed example, applied in the case-study, is reported in the Supplementary Material.

The primary technological scenarios following the LOC event then are characterized in terms of frequency (f_P) and consequences by the application of specific event trees, conceptually analogous to those obtained in the conventional assessment of technological scenarios following a release [15,18]. For instance, in the case of floods, water-reacting substances might give rise to specific scenarios after the release, which were object of previous studies [58].

The identification of further equipment items that may be the possible secondary targets of domino effects generated by the primary scenarios (Step 3 in Figure 1) is then performed by means of well-established threshold-based screening methodologies applied to the escalation vectors generated by the primary technological scenarios [59–61]. It should be remarked that past accident analysis evidenced that most Natech events reported in the literature and in industrial accident databases involved the release of flammable chemicals [12,58,62], which may lead to domino effect due to fire escalation in case of ignition. Thus, in the following, the methodology was focused on domino effects generated by the escalation of fire scenarios. Nevertheless, the methodology may be applied as well to other escalation vectors, when relevant (e.g., fragment projection or blast waves).

A thorough assessment of the effect of safety barriers on the likelihood of escalation considering the impact of the natural event on these measures is then required (Steps 4-5 in Figure 1). A multi-level quantitative methodology specifically addressing the Natech framework is developed to consider the presence and performance of safety barriers in the assessment of escalation likelihood. Considering barrier complexity and uncertainties related to the intensity and impact of natural hazards, three levels of assessment are conceptualized, as shown in Figure 1 (Steps 5a to 5c). The approach proposed will be described in detail in Section 3.2.

Probabilistic assessment of domino event frequencies can then be performed (Step 6 in Figure 1). The probability of escalation of stationary fires is evaluated by means of probit models based on the time to failure (*ttf*) of target vessels when impacted by the heat load [16,37,63]. Probabilities and frequencies of the final events are then assessed applying a dedicated event tree (ETA) methodology, which was specifically developed in earlier studies to include safety barriers in the modelling of escalation [40,64,65]. The model allows for the characterization of both unmitigated and mitigated secondary scenarios, based on barrier performance. Further details on fire escalation models and ETA methodology are reported in the Supplementary Material.

The following step of the methodology is the consequence assessment of the secondary domino scenarios (Step 7 in Figure 1), which is carried out adopting literature models [66–68]. In order to obtain a less conservative description of the secondary scenarios, the consequences of mitigated events are modelled considering the mitigation action of the safety barriers, as described in detail in the Supplementary Material.

The final steps of the methodology (Steps 8-10 in Figure 1) involve the characterization of the overall domino scenarios and are described in Section 3.3. The analysis can be extended to the identification and assessment of tertiary events and/or higher level events. In case, the procedure is applied recursively and the selection of possible tertiary/higher level targets possibly affected by escalation needs to be carried out [16,40]. Risk index calculation may be carried out (Step 11 in Figure 1) using the standardized procedures reported in Section 3.4.

3.2 Quantitative assessment of safety barrier performance modification in Natech scenarios

The concept of safety barriers is extensively used in the chemical and process industry referring to physical and non-physical means implemented to reduce the possibility of technological accidents or to lessen their impact [69–71]. A well-established classification of safety barriers, particularly suitable within the framework of QRA, is based on barrier working principle and is summarized in Table 1 [64,70,72,73].

Table 1: Summary of barrier classification based on working principle [73]*, applied in the present study.*

Classification	Description	Examples
Passive barriers	All the physical protections available in the plant, which do not require any activation to perform their function	Fireproofing, catch basins, pressure safety valves (PSV), sumps, mounds, firewalls, blast walls
Active barriers	Complex systems requiring external automatic and/or manual activation to perform their function	Foam-water systems (FWS), sprinklers, water deluge systems (WDS), emergency shutdown (ESD), emergency blowdown (EBD)
Procedural barriers	Emergency intervention procedures and structured plans for managing and controlling scenarios	Internal/external emergency team intervention, fire brigade intervention, evacuation plans

Performance of safety barriers can be assessed through specific methodologies or retrieving generic data from reliability databases [74–76]. Moreover, methodologies are available in the literature to tailor failure frequencies of equipment items and to include the effect of specificities and environmental factors on reliability figures [77–79]. For instance, general failure frequencies may be revised through expert judgment in order to include the effect of item location and other factor not accounted in database values [79]. Proportional hazard models (PHM) have been applied to include the effect of explanatory variables (i.e., covariates) in modification of equipment failure rate and reliability [77,80,81]. More recently, covariate-based models have been applied to evaluate the impact of harsh environment conditions on technical systems availability [78,82]. However, none of these methodologies explicitly address the possibility of performance modification during Natech accidents [83].

Therefore, a novel methodology for the assessment of safety barrier performance modification during Natech accidents was developed. The methodology is based on the preliminary evaluation of baseline barrier performance, not accounting for the influence of the natural hazards (Step 4 in Figure 1), through a tailored LOPA approach developed in the context of domino escalation assessment [64,65]. Each safety barrier is categorized according to Table 1. The performance of each barrier is then expressed through a two-parameter metrics: i) the probability of failure on demand (*PFD*), that is the probability that the measure will not be available when required to perform the safety function, and ii) the effectiveness (η), that is, the conditional probability the barrier is able to prevent (or stop) domino escalation once successfully activated. The *PFD* is linked to barrier system architecture and reliability, and may be determined by means of various reliability approaches according to the available information on the system components, as extensively discussed elsewhere [64,84]. On the other hand, η is the direct quantification of the quality of barrier mitigation or preventive actions, hence it should be estimated considering performance data or statistics, together with other influencing factors as maintenance, operational management and so forth [40,64,65].

Once the baseline probabilistic performance of safety barriers is estimated, barrier performance modification due to the natural hazard considered is then assessed, according to a three-level methodology (i.e., Level 0, Level 1, and Level 2 in Step 5 of Figure 1). Level 0 (L0) is based on a simplified evaluation suitable for simpler barrier systems (Step 5a indicated in green in Figure 1). Level 1 (L1) in the assessment is based on the data obtained for reference schemes of safety barriers in previous studies [83] (Step 5b in Figure 1). Level 2 (L2) is based on a detailed analysis of barrier architecture and subsystems, capable of accounting for site-specific scenarios and special design provisions (Step 5c in Figure 1). The three levels of assessment are introduced to address barrier systems with increasing level of complexity, thus require an increasing amount of information to be applied. Clearly enough, the selection of the level of the analysis is related to the uncertainty on the possible interaction between the reference natural hazard and the specific features of the barrier under consideration, as explained in the following.

The basic barrier performance modification assessment level, L0, is adequate when a low uncertainty is present concerning the definition and quantification of the impact of natural hazards on the barrier. This level is conceptually similar to the application of a single-covariate PHM [78,80] and can be regarded as a Boolean approach. In this case the covariate is a feature of the barrier (e.g., the position), identifiable by means of rules-of-thumb or basic evaluations, which justify with confidence whether the barrier should be considered affected or not by the natural hazard considered. In case the k-th barrier is considered unaffected, it will retain the baseline performance values $PFD_{0,k}$ and $\eta_{0,k}$ while in case the covariate indicates the system would be clearly impacted, the k-th barrier should be considered unavailable. In the two-parameter metrics, this is equivalent to setting $PFD_{j,k} = 1$ for active systems and $\eta_{j,k} = 0$ for passive protections.

Level L1 assessment is required where some uncertainty concerning barrier performance is present. This level is an application of the PHM to the two-parameter metrics and is suitable for a wide class of barriers, from passive barriers to the simpler active systems. Modified barrier performance is described by means of a covariate, namely a performance modification factor (ϕ), representing the likelihood that similar reference barriers would fail directly due to the natural event, as proposed in a previous study [83]. It is assumed that the failure mode of active barriers is the lack of activation, leading to barrier unavailability: thus, an increase in the PFD should be considered for this type of barriers. In case of passive barriers, the effectiveness η may be reduced by the impact of the natural event, due to the possible loss of structural integrity of the barrier or to other causes (e.g. in case of flood, catch basins will not be effective in the retention of spills).

Hence, in the case of an active barrier, performance parameters are modified according to Eqs. (2) and (3) [82]:

$$PFD_{j,k} = 1 + (\phi_{j,k} - 1)(1 - PFD_{0,k}) \tag{2}$$

$$\eta_{j,k} = \eta_{0,k} \tag{3}$$

where $\phi_{j,k} \in [0,1]$ is the performance modification factor of the k-th active barrier for j-th reference natural hazard scenario, and $PFD_{0,k}$ and $\eta_{0,k}$ are the baseline performance parameters of the k-th active barrier determined in Step 4 of the methodology of Figure 1.

In the case of a passive barrier, a different modification of performance parameters is introduced:

$$\eta_{j,k} = (1 - \phi_{j,k})\, \eta_{0,k} \tag{4}$$

where $\phi_{j,k} \in [0,1]$ is the performance modification factor for j-th reference natural hazard scenario, and $\eta_{0,k}$ is the baseline effectiveness value, determined in Step 4 of the methodology of Figure 1.

Suggested value for performance modification factors, obtained by an expert survey, are available in the literature [13].

The L2 level assessment is required when complex active barrier systems are considered, where the actual consequences of the impact of the reference natural hazard are affected by a high uncertainty. The assessment may also be applied to barriers where the specific system architecture may differ from that of reference configurations, and performance modification factors may not be applicable with confidence. This level of analysis is based on a fault tree analysis (FTA) focused on the possible failure of subsystems due to the impact of the natural hazard. Indeed, after the construction of the fault tree considering barrier architecture, the minimal cut sets (MCSs) are identified and basic events are screened to explicitly identify which might be influenced by the impact of the natural hazard. The analysis should be performed, considering detailed information on barrier subsystems, including position, fail-safe design, dependence on lifelines, and redundancies. After vulnerable barrier subsystems are identified, the probabilities of the related basic events in the fault tree are updated to unitary values (i.e., indicating expected subsystem failure during the reference natural scenario). Therefore, considering the m-th MCS of the k-th barrier, its updated probability during the j-th reference natural scenario $Q_j(MCS_{m,k})$ can be assessed through Eq. (5):

$$Q_j(MCS_{m,k}) = \prod_p (q_{p,0} + \delta_{p,j}(1 - q_{p,0})) \quad (5)$$

where $q_{p,0}$ is the probability of the p-th basic event comprised in the m-th MCS, and the parameter $\delta_{p,j}$ is equal to 1 in case the p-th basic event involves one of the vulnerable barrier subsystems identified (for the j-th reference natural scenario), and 0 if not. Conservatively, the updated PFD of the k-th barrier, $PFD_{j,k}$, can then be recalculated (as an upper bound) according to Eq. (6):

$$PFD_{j,k} = 1 - \prod_m (1 - Q_j(MCS_{m,k})) \quad (6)$$

Therefore, the output of the L2 level assessment is a scenario-based quantification of barrier updated unavailability in case the reference natural event will impact the site, calculated considering the impact on each system component.

The application of each of the three levels of barrier assessment will be exemplified in the analysis of the case study, providing further details on the assessment procedure (see Section 5.1 and Appendix A).

Due to the high site-specificity of procedure and emergency response actions, no generalised methodology was developed for the assessment of procedural barriers. A case-by-case assessment is recommended, analysing and assessing how the natural hazard may influence each key procedural step. In the analysis of the case study, a simplified approach is proposed to address the possible failure or delay of first response actions by emergency teams [64,65].

The modified barrier performance parameters obtained by the highest level of assessment, L2, should then be implemented in ETA through specific logical operators [64,65]. These operators are represented as gates on the event trees addressing accident escalation, and influence how each of the barriers contributes to the modification of the probabilities and frequencies of the final domino events. Details on logical operators and on their implementation in ETA are reported in the Supplementary Material.

3.3 *Characterization of overall domino scenarios*

According to the ETA defined in barrier performance analysis (e.g., see Section 5), each target equipment can show one out of three possible final events, in agreement with the approach described in [14,40]:

- State "2": unmitigated secondary domino scenarios, in case all the protection barriers implemented have failed and is clearly a worst-case being the outcome with the most severe consequences;
- State "1": mitigated secondary domino scenarios, that is, intermediate situations occurring when part of the safety barrier implemented fails in stopping escalation, leading to scenarios with potentially reduced consequences due to partial activation or reduced effectiveness of safety barriers in the accident sequence
- State "0": no domino scenarios, in which the escalation is interrupted due to activation and effective response of the safety barriers.

The peculiarity of mitigated scenarios is that their consequences might be less severe than unmitigated scenarios, and this feature should be considered for a more accurate risk evaluation. A detailed characterization of mitigated secondary domino scenarios proposed in a previous study [40] might be adopted to account for the specificities of the type of target, the barriers considered and the emergency strategy pursued (see the Supplementary Material for further details). The proposed approach is exemplified in the case-study application (see Section 5.2).

Once the complete set of the secondary escalation scenarios is characterized, frequency assessment and consequence evaluation of overall domino scenarios can be performed (Steps 8-10 in Figure 1). Considering the escalation logic with m possible states for each of the n secondary domino targets, the number of different secondary domino scenarios from a primary Natech scenario (N_c) can be determined as follows:

$$N_c = \prod_{i=1}^{n} m_i \tag{7}$$

where m_i is the number of possible outcomes for the *i-th* secondary target, assuming that all the targets have three possible escalation states, $N_c = 3^n$. The probability of overall final domino scenarios can thus be assessed assuming that a specific secondary outcome for a given target is independent from that of the other target units, as it is assumed in previous studies addressing escalation due to domino effect [16,38].

Indeed, each overall final scenario $\boldsymbol{C}^n$ can be represented as a vector of n elements indicating the combination of the events involving each of the n possible domino targets. Defining $\boldsymbol{C}_i^n$ as the generic element of $\boldsymbol{C}^n$ that represents the final event of the generic *i-th* target, the joint probability of the generic overall final scenario $P(\boldsymbol{C}^n)$ might be calculated as follows:

$$P(\boldsymbol{C}^n) = \prod_{i=1}^{n} P(\boldsymbol{C}_i^n) \tag{8}$$

where $P(\boldsymbol{C}_i^n)$ is the probability of the state of the *i-th* target, assessed during with the ETA.

The frequency of each generic $\boldsymbol{C}^n$ can then be calculated starting from the frequency of the primary Natech scenario generating the domino escalation f_P according to:

$$f(\boldsymbol{C}^n) = f_P \times P(\boldsymbol{C}^n) \tag{9}$$

In order to complete the characterization of overall domino scenarios, once the frequency assessment is performed, the consequence analysis and the calculation of risk indexes should be carried out (Steps 10 and 11 in Figure 1). Since no relevant difference is present with respect to conventional domino scenarios, the method proposed in [39] is applied to these steps. Details are provided in the Supplementary Material.

3.4 *Risk calculation and risk metrics*

Once overall domino scenarios are characterized, the calculation of overall risk level may be performed (Step 11 in Figure 1). Individual risk can be expressed by mapping local specific individual risk (LSIR) following standardized procedures, while societal risks can be expressed with F/N plots, being F is the cumulative frequency of scenarios causing N or more expected fatalities, which is calculated directly from the frequency f of scenarios causing N fatalities [67,68,85]. Two further risk indices were selected to provide an overall quantification of risk: the Potential Life Loss (PLL) and the Expectation Value (EV), which are calculated according to Eqs. (10) and (11) respectively:

$$PLL = \sum_N f(N)N = \sum_N F(N) \tag{10}$$

$$EV = \sum_N f(N)N^a \ with\ a = 2 \tag{11}$$

4. Case study

4.1 Definition of case studies

The equipment lay-out considered in the case study in shown in Figure 2. The layout includes nine atmospheric storage tanks (T01-T09 in Figure 2), and four pressurized vessels (P01-P04 in Figure 2). The details of the equipment items are summarized in Table 1.

Figure 2: Layout considered in the case study. Tank T01 (in red) is considered to generate the primary Natech scenario. All other items are considered as possible domino targets. Equipment features are summarized in Table 2.

In order to exemplify the methodology, a single flooding scenario was selected as the reference natural hazard: a flood with a time of return of 500 years ($f_w = 2.00 \times 10^{-3}$ y^{-1}), characterized by a water depth, $h_{w,}$ of 2.0 m and a speed, $v_{w,}$ of 1.0 m/s was assumed. It should be noted that despite in this case study a flood scenario is considered, the methodology allows addressing also other types of natural hazards (e.g., earthquakes, etc.).

Table 2: Equipment items considered in the case study (see Figure 2 for layout representation; D = Diameter; H = height; m_t = stored mass; p_o = operating pressure; V_n = nominal volume; ρ_L = liquid density; ρ_V = vapour density).

ID	D [m]	H [m]	V_n [m^3]	Substance	ρ_L [kg/m^3]	ρ_V [kg/m^3]	p_o [bar]	m_t [t]
T01	*30*	*7.2*	*5087*	*Gasoline*	*750*	-	*1.01*	*2860*
T02	30	7.2	5087	Gasoline	750	-	1.01	2860
T03	30	7.2	5087	Gasoline	750	-	1.01	2860
T05	24	9	4069	H_2S (0.4% mol in H_2O)	1100	-	1.01	3360
T04	28	9	5539	Benzene	820	-	1.01	3410
T06	20	10.8	3391	NaCl (1% mol in H_2O)	1050	-	1.01	2670
T07	20	10.8	3391	NaCl (1% mol in H_2O)	1050	-	1.01	2670
T08	28	9	5539	Benzene	820	-	1.01	3410
T09	28	9	5539	Benzene	820	-	1.01	3410
P01	3.4	22	192	Propane	497	18.9	8.4	86.3
P02	3.4	22	192	Propane	497	18.9	8.4	86.3
P03	3.4	22	192	Propane	497	18.9	8.4	86.3
P04	3.2	22	170	Ammonia	600	4.9	8.5	91.9

Since the aim of the case-study is not to perform a complete QRA, but rather to show the contribution of specific barrier performance modifications on the overall risk figures, a single primary scenario is considered to be generated by the flood for the sake of simplicity. Clearly enough, the methodology is able to consider also the escalation of multiple primary scenarios, resulting from the damage of more than a single tank.

In the specific case-study presented, it is assumed that tank T01, storing gasoline, is the only process unit damaged by the flood. The catastrophic failure of tank T01 starting a pool fire [58] is considered. The damage probability of the tank, $P_{nhd}(T01)$, calculated by the vulnerability model reported in the Supplementary Material, is estimated at 0.411. A conservative value of 0.9 is assumed as the ignition probability following the loss of containment (LOC), as suggested in the literature [17]. Hence, the resulting frequency of the primary Natech scenario is obtained as the product of $f_{I,LOC}$, calculated according to Eq. (1), and the assumed ignition probability, resulting in $f_P = 7.395 \times 10^{-4}$ y^{-1}.

To further simplify the interpretation of results, four cases were considered in the following:

- Case 1: only the primary Natech scenario described above is considered, to define a baseline risk associated to the impact of the flood on tank T01;
- Case 2: also the possible escalation scenarios due to domino effect are considered. Probability of escalation is calculated not considering the action of safety barriers. This case thus represents a reference worst-case scenario.
- Case 3: as case 2, but probability of escalation is calculated considering the action of safety barriers. Baseline values are considered for barrier performance [40]. This case represents the best option for the expected performance of safety barriers, since the possible effects of the impact of the natural hazard on the safety barriers are neglected;
- Case 4: as case 3, but barrier performance degradation due to the impact of the flood is considered by the methodology presented in Section 3.2.

Moreover, in order to compare the risk due to Natech scenarios triggered by flooding to the risk caused by "conventional" releases from tank T01, a baseline case was also defined (case 0). This case enables the assessment of a baseline "conventional" risk associated with tank T01, thus without considering the contribution of the Natech event. The analysis of case 0, based on consolidated guidelines for risk assessment [85], is documented in the Supplementary Material.

Consequence assessment was performed by means of well-established literature models for physical effect modelling [66–68]. For the sake of simplicity, a uniform wind distribution and a single set of meteorological conditions have been assumed. In particular, wind speed was assumed at 5 m/s, neutral atmospheric stability was considered (class D) [66,85]. Atmospheric temperature was assumed at 20°C and relative humidity at 70%. Clearly enough, different meteorological conditions may be considered in the assessment.

In order to model human vulnerability to the physical effects of accidents, literature vulnerability models (i.e., probit and threshold-based) were applied, as detailed in the Supplementary Material. A fictitious uniform population density was assumed to obtain representative societal risk figures not affected by local-specific effects. The population density value, equal to 200 people/ha^2 with 60% presence probability, was considered constant over the entire impact area. For the sake of simplicity, no evacuation was considered and the population was assumed to be affected only by the consequences of the technological scenarios. Risk calculation was performed applying the methodology presented in [46,86]. Alternative approaches are obviously possible for the calculation of the risk indexes considered [68].

For the sake of brevity, only the probabilistic assessment of case 4 will be detailed thoroughly in the following, limiting the presentation of cases 1, 2 and 3 to the discussion of the results. The complete description of the procedure applied to the analysis of the latter cases is reported in the Supplementary Material.

4.2 Domino effect assessment and safety barriers

In order to identify the possible targets for domino escalation, a threshold-based methodology was applied, considering the heat radiation from the primary Natech accident as the possible escalation vector. The threshold criteria selected to assess the credibility of escalation are 15 kW/m^2 for atmospheric equipment and 45 kW/m^2 for pressurized tanks, as suggested in specific studies [60,61]. As shown in Table 3, four possible escalation targets were identified: two atmospheric tanks (tanks T02 and T05 in Figure 2), and two pressurized vessels (vessels P03 and P04 in Figure 2).

Table 3 also lists the safety barriers associated to each possible target. All the targets identified are equipped with pressure safety valves (PSVs). Tanks T02 and T05 are equipped with foam-water systems (FWS), while vessels P03 and P04 are protected by water deluge systems (WDS). The main assumptions considered for FWS and WDS architectures are reported in Appendix A. As additional layer of protection, passive fire protection (PFP) is also considered for vessels P03 and P04. Beside the technical barriers (both active and passive), external emergency intervention (EEI) is always considered.

Table 3: Escalation targets with assumed set of safety barriers (PSV=pressure safety valve; FWS=foam-water system; WDS=water deluge system; PFP=passive fire protection (fireproofing); EEI=external emergency intervention).

Target	**Radiation from T01 [kW/m^2]**	**PSV**	**FWS**	**WDS**	**PFP**	**EEI**
T02	43.3	X	X			X
T05	26.5	X	X			X
P03	57.5	X		X	X	X
P04	82.5	X		X	X	X

5. Results and Discussion

5.1 Assessment of safety barriers performance in Natech events

The assessment of safety barrier performance is summarized in Table 4. For each barrier, the original performance values are reported (these are adopted in case 3), together with the classification according to Section 3.2. Barrier performance is modified according to one of the three levels of analysis, as indicated in the table.

In particular, L0 analysis is applied to the PSVs, since these components may be considered unaffected by the flooding scenario. This can be assessed with sufficient confidence, since the PSV is a single-hardware device located on top of the equipment items and its action does not depend on utilities as instrument air or electricity.

Table 4: Barrier performance assessment and modification. 0=original performance, f=performance during the reference flood event. Barrier coding is defined according to Table 3.

Barrier	**Classification**	**Gate**[a]	PFD_0	η_0	**Level of Analysis**[c]	PFD_f	η_f
PSV	Passive	a	1.00E-02	1.00	L0	1.00E-02	1.00
FWS	Active	b	5.42E-03	9.54E-01	L2	1.00	9.54E-01
WDS	Active	a	4.33E-02	1.00	L2	1.00	1.00
PFP	Passive	a	0	9.99E-01	L1	0	8.49E-01
EEI	Procedural	c	1.00E-01	0;1	n.a.	1.00E-01	0;1[b]

[a] Gates are defined in the Supplementary Material.
[b] Based on the comparison between time to failure and time to final mitigation, calculated according to Supplementary Material.
[c] Analysis level selected in Step 5 in Figure 1.

The L1 analysis was applied to assess the performance of the passive fire protection (PFP). This choice is due to the limited complexity of the barrier, not requiring the application of a more complex level of analysis. Nevertheless, the PFP might be impacted by the natural event and a performance modification factor $\phi_{f,PFP} = 0.15$ retrieved from an expert survey [13] was thus adopted to modify barrier effectiveness according to Eq. (4), obtaining $\eta_{f,PFP} = 8.49 \times 10^{-1}$ (see Table 4).

The L2 analysis was applied to the foam-water system (FWS), since this is a complex active barrier for which a deeper understanding of how the flood might impact barrier subsystems is required to determine the expected reliability during the Natech event. Therefore, FTA was carried out, considering the main components characterizing the architecture of the barrier system, which is reported in Figure 3. The values reported in Figure 3 were obtained from literature sources and express the expected event frequency considering original component unavailability $q_{p,0}$ [67,87–91]. The contribution of common cause failure is included through a 5% beta factor in PFD_0 [67]. The values were used to determine PFD_0 (i.e., original barrier performance).

The FTA was then examined to identify the subsystems and components critically impacted by the reference flood scenario. In Figure 3 the most vulnerable nodes identified are highlighted in red. The probability of these events is updated to a unitary value since the involved subsystems/components are expected to be not available during the reference flood scenario (i.e., $\delta_p = 1$ for the probability of events reported in red in the quantification of MCSs). Then, the FTA is quantified and an updated value of the PFD in case of flood, PFD_f, is calculated by means of Eqs. (5) and (6). The PFD_f value is then used in the quantitative ETA.

As shown in Figure 3, the main contribution to the unavailability of the FWS is given by the lack of electricity. Besides, during floods the main power connections are likely to fail due to power grid disruption [92], and, also considering the relevant water height of the flooding scenario considered (h_w = 2.0m), the backup diesel generators, located at ground level to reduce vibrations, are likely to be submerged. It is relevant to remark that in past Natech accidents involving flooding with relevant water depths, backup supply generators have been affected, not being designed to resist to high impact flooding scenarios [8,93]. Moreover, jockey pumps and diesel pumps are likely to be submerged as well. Electric cables and connections are also an issue, although they are usually well insulated and may be unaffected by the flooding [94]. Therefore, considering the architecture of the FWS reported in Figure 3 and the updated unavailability of the vulnerable components, the PFD_f resulting from FTA quantification by means of Eqs. (5) and (6) is unitary and the safety barrier is thus considered not available during the Natech accident.

A similar procedure was used to apply L2 analysis to WDS. For the sake of brevity, the FTA of WDS is presented in Appendix A. Considering the updated values for the unavailability of the vulnerable system components in case of flood, the analysis led to a unit value for PFD also in the case of WDS. Hence, the WDS is deemed not available during the reference flood scenario assumed in the case-study.

As discussed in Section 3.2, a specific assessment is required by the assessment of procedural and emergency barriers. The specific procedure proposed in [64,65] was applied to address the performance of EEI. Accordingly, the effectiveness of EEI should be determined considering the comparison of target time to failure (*ttf*) and required time for final mitigation (*tfm*). Further details are available in the Supplementary Material. On the basis of primary fire features and target geometry [64], the *tfm* is estimated at 65 min and 90 min respectively for pressurized vessels (i.e., vessels P03 and P04) and atmospheric storages (i.e., tanks T02 and T05).

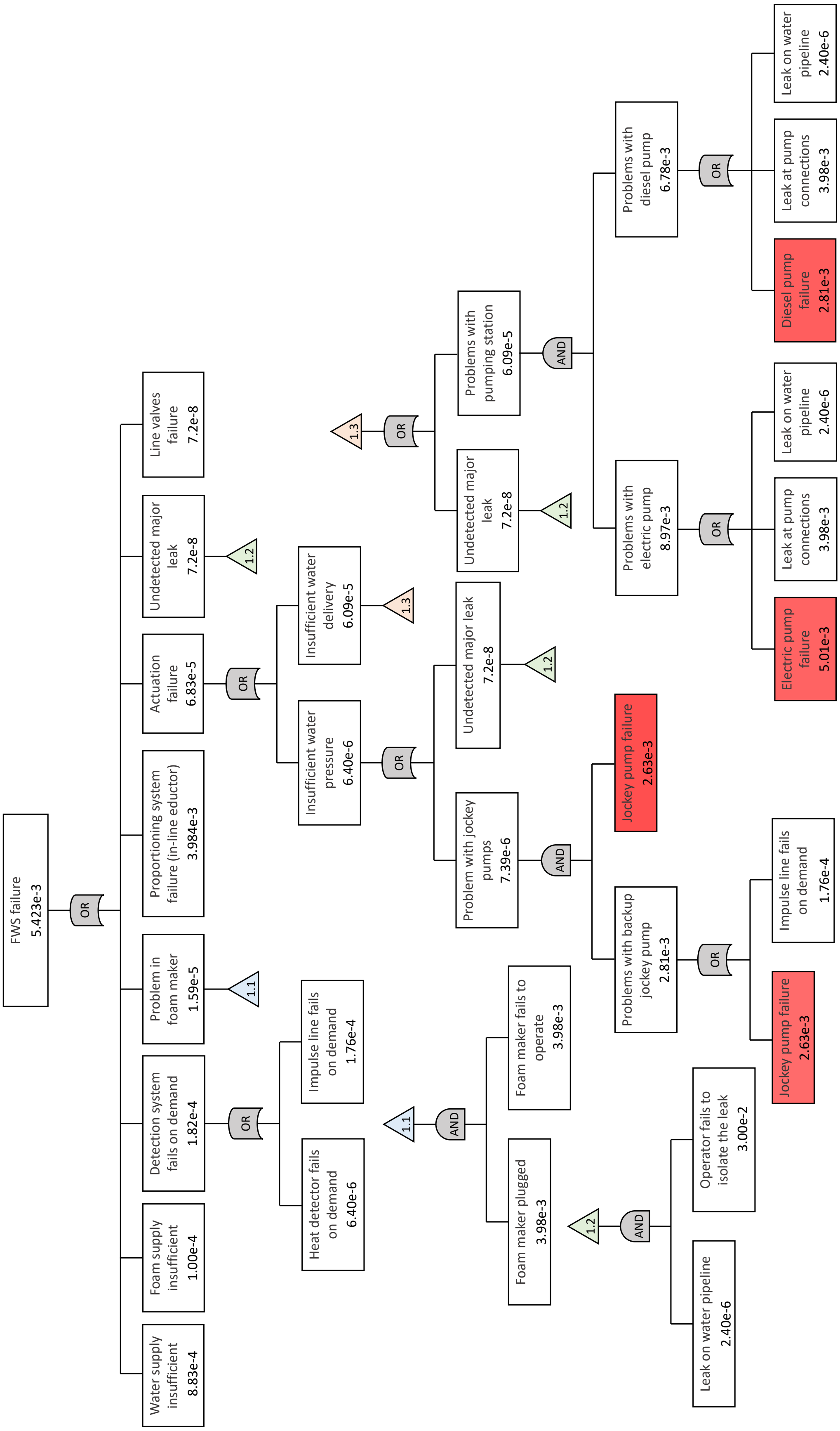

Figure 3: Fault tree for the foam-water system (FWS) considered in the case study. Values reported are the baseline unavailability values $q_{p,0}$ which have been used to quantify baseline barrier PFD_0 and updated PFD_f, according to Eqs. (5) and (6). Basic events involving components/subsystems which are deemed not available during the reference flooding scenario are highlighted in red.

5.2 *Assessment of the final outcomes of secondary scenarios*

The modified ETA approach presented in Section 3.2 (and detailed in Supplementary Material) was applied to the identification of the final outcomes of the secondary scenarios caused by domino effect, considering the safety barriers in place and their performance as assessed in Section 5.1. The event trees obtained for tank T02 and vessel P03 are reported in Figure 4. The probabilistic assessment of these secondary scenarios is reported in Table 5 (tank T02) and Table 6 (vessel P03), while for the sake of brevity the ETs and the results from the probabilistic assessment of domino scenarios for tank T05 and vessel P04 are reported in the Supplementary Material.

Table 5: Probabilistic assessment of the final outcomes of secondary scenarios caused by domino effect for tank T02. Final outcomes with frequency equal to zero are not reported.

Final outcome	Escalation scenario	Secondary final outcome	Probability	Frequency [y^{-1}]
FO_T02_01	Unmitigated domino	Pool fire, maximum emissive power	9.49E-04	7.02E-07
FO_T02_02	Unmitigated domino	No escalation	5.07E-05	3.75E-08
FO_T02_03	Mitigated domino	Pool fire, mitigated emissive power	8.54E-03	6.32E-06
FO_T02_04	Mitigated domino	No escalation	4.56E-04	3.37E-07
FO_T02_05	Mitigated domino	Pool fire, maximum emissive power	9.40E-02	6.95E-05
FO_T02_06	Mitigated domino	No escalation	5.02E-03	3.71E-06
FO_T02_07	Mitigated domino	Pool fire, mitigated emissive power	8.46E-01	6.25E-04
FO_T02_08	Mitigated domino	No escalation	4.52E-02	3.34E-05

Table 6: Probabilistic assessment of the final outcomes of secondary scenarios caused by domino effect for tank P03. Final outcomes with frequency equal to zero are not reported.

Final outcome	Escalation scenario	Secondary final outcome	Probability	Frequency [y^{-1}]
FO_P03_01	Unmitigated domino	Fireball	5.11E-05	3.78E-08
FO_P03_02	Unmitigated domino	No escalation	9.97E-05	7.38E-08
FO_P03_03	Mitigated domino	Fireball	4.60E-04	3.40E-07
FO_P03_04	Mitigated domino	No escalation	8.98E-04	6.64E-07
FO_P03_05	Mitigated domino	Fireball	3.88E-08	2.87E-11
FO_P03_06	Mitigated domino	No escalation	8.49E-04	6.28E-07
FO_P03_07	No domino	No escalation	7.64E-03	5.65E-06
FO_P03_15	Mitigated domino	Fireball	5.06E-03	3.74E-06
FO_P03_16	Mitigated domino	No escalation	9.88E-03	7.30E-06
FO_P03_17	Mitigated domino	Fireball	4.55E-02	3.37E-05
FO_P03_18	Mitigated domino	No escalation	8.89E-02	6.57E-05
FO_P03_19	Mitigated domino	Fireball	3.84E-06	2.84E-09
FO_P03_20	Mitigated domino	No escalation	8.41E-02	6.22E-05
FO_P03_21	No domino	No escalation	7.57E-01	5.59E-04

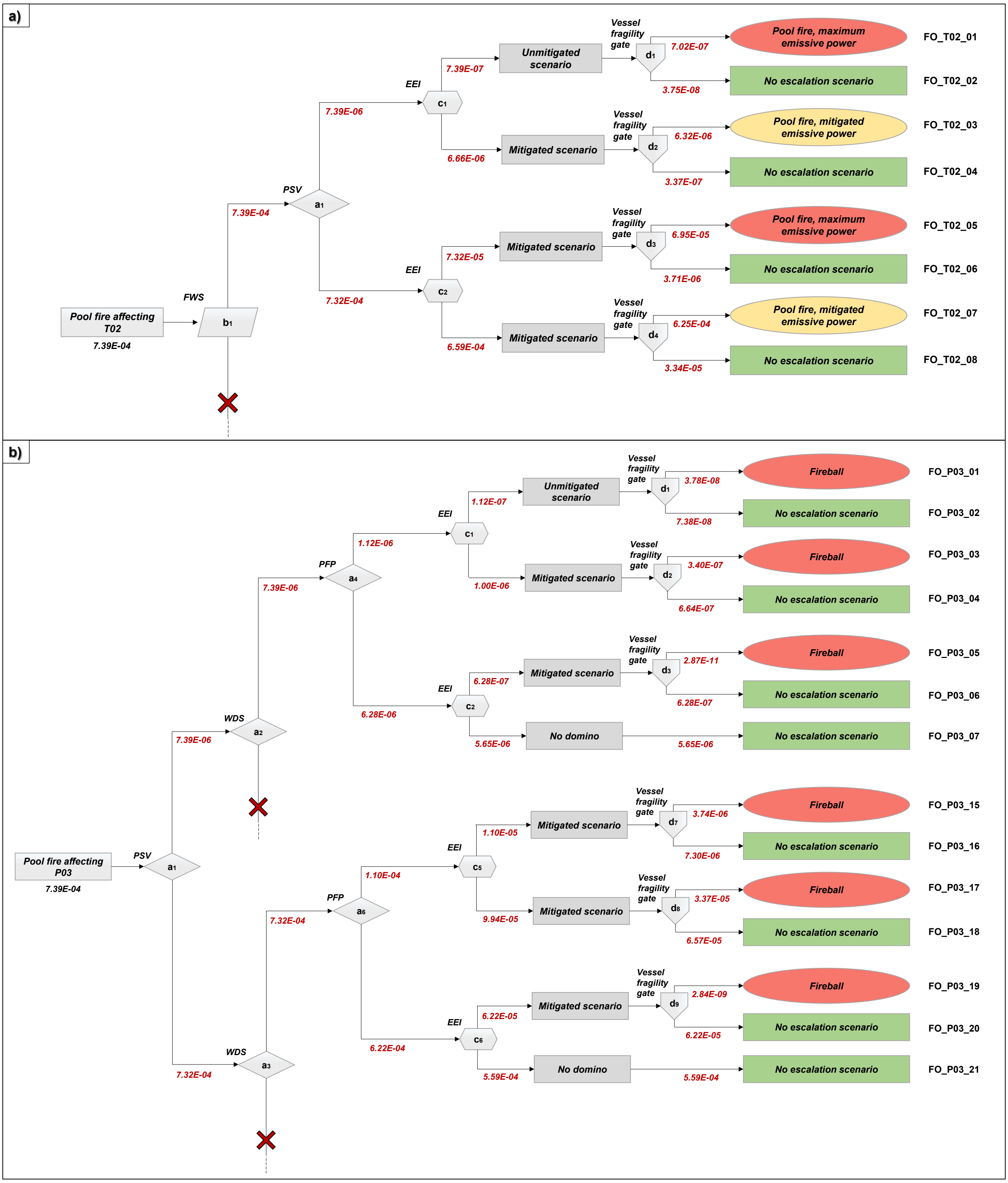

Figure 4: Event trees reporting the quantification of the frequencies (in y^{-1}) of final outcomes of: a) escalation scenarios involving tank T02 and b) escalation scenarios involving vessel P03. The branches indicated with a red cross are not further considered, as consequence of the failure of FWS (in panel a) and WDS (in panel b) caused by the flooding, as indicated by FTAs in L2 analysis. FO= Final Outcome.

As shown in Figure 4, the application of the barrier assessment methodology (Step 5 in Figure 1) results in the elimination of part of the ETA branches. In particular, the downward output branches of the logic operators associated to the FWS (node b_1 in Figure 4-a) and WDS (nodes a_2 and a_3 in Figure 4-b) systems are no more present, since these two systems are considered unavailable during the reference flood scenario according to the results obtained from L2 analysis.

Thus, the methodology led to the identification and characterization of the set of final outcomes reported in Table 7. The table also reports the calculated frequencies and probabilities of the final outcomes. As shown in the table, mitigated scenarios (indicated with number "1" in the column "State" of the table) are not considered likely for the pressurized equipment items, as the vessels P03 and P04. Indeed, in the case of escalation caused by domino effect due to a fire involving pressurized equipment, the action of fire brigades may not be able to mitigate the violent vaporization of the fluid, as described in Supplementary Material.

Table 7: Probabilities and frequencies of the final outcomes identified through the ETA. State (see Section 3.3): 0=no escalation; 1=mitigated escalation; 2=unmitigated escalation. SEP=surface emissive power.

Target	**State**	**Secondary final event**	**Probability**	**Frequency [1/y]**
T02	0	No scenario	5.070E-02	3.749E-05
T02	1	Pool fire, mitigated SEP	8.544E-01	6.318E-04
T02	2	Pool fire, max SEP	9.493E-02	7.020E-05
T05	0	No scenario	2.873E-01	2.124E-04
T05	1	Toxic dispersion, mitigated evaporation rate	6.514E-01	4.744E-04
T05	2	Toxic dispersion, maximum evaporation rate	7.127E-02	5.271E-05
P03	0	No scenario	9.489E-01	7.017E-04
P03	2	Fireball	5.110E-02	3.779E-05
P04	0	No scenario	9.072E-01	6.708E-04
P04	2	Toxic dispersion	9.281E-02	6.863E-05

5.3 *Assessment of the overall domino scenarios*

Starting from the final outcomes of the secondary events reported in Table 7, the number of different overall domino scenarios is determined by Eq. (7). Considering that escalation involving tanks T02 and T05 can lead to three alternative final outcomes each, while in the case of vessels P03 and P04 two alternative final outcomes are only possible, the number of overall domino scenarios, N_C, is equal to 36. For the sake of simplification, only secondary domino scenarios are considered in the case study. Nevertheless, the proposed methodology is recursively applicable for further level assessment, as it is explained in Section 3 (see Figure 1).

The probabilities and frequencies of the overall domino scenarios are assessed applying Eqs. (8) and (9), as described in Section 3.3. The results are presented in Table 8. As shown in the table, the frequencies of the overall scenarios span between 10^{-8} to 10^{-4} y^{-1}, and many combinations have probability values close to that of the primary Natech scenario, as well as to the conventional scenarios considered as benchmarks.

Table 8: Overall domino scenarios (final event combinations) considered for risk assessment. State (see Section 3.3): 0=no escalation; 1=mitigated escalation; 2=unmitigated escalation.

ID	**Target state**				**Probability**	**Frequency [1/y]**	**ID**	**Target state**				**Probability**	**Frequency [1/y]**
	T02	**T05**	**P03**	**P04**				**T02**	**T05**	**P03**	**P04**		
1	0	0	0	0	1.254E-02	9.270E-06	19	0	0	0	2	1.283E-03	9.484E-07
2	0	1	0	0	2.800E-02	2.070E-05	20	0	1	0	2	2.864E-03	2.118E-06
3	0	2	0	0	3.111E-03	2.300E-06	21	0	2	0	2	3.182E-04	2.353E-07
4	1	0	0	0	2.113E-01	1.562E-04	22	1	0	0	2	2.161E-02	1.598E-05
5	1	1	0	0	4.718E-01	3.489E-04	23	1	1	0	2	4.827E-02	3.569E-05
6	1	2	0	0	5.242E-02	3.876E-05	24	1	2	0	2	5.363E-03	3.966E-06
7	2	0	0	0	2.347E-02	1.736E-05	25	2	0	0	2	2.402E-03	1.776E-06
8	2	1	0	0	5.242E-02	3.876E-05	26	2	1	0	2	5.363E-03	3.966E-06
9	2	2	0	0	5.824E-03	4.307E-06	27	2	2	0	2	5.959E-04	4.406E-07
10	0	0	2	0	6.752E-04	4.993E-07	28	0	0	2	2	6.907E-05	5.108E-08
11	0	1	2	0	1.508E-03	1.115E-06	29	0	1	2	2	1.542E-04	1.141E-07
12	0	2	2	0	1.675E-04	1.239E-07	30	0	2	2	2	1.714E-05	1.267E-08
13	1	0	2	0	1.138E-02	8.414E-06	31	1	0	2	2	1.164E-03	8.608E-07
14	1	1	2	0	2.541E-02	1.879E-05	32	1	1	2	2	2.599E-03	1.922E-06
15	1	2	2	0	2.823E-03	2.088E-06	33	1	2	2	2	2.888E-04	2.136E-07
16	2	0	2	0	1.264E-03	9.349E-07	34	2	0	2	2	1.293E-04	9.564E-08
17	2	1	2	0	2.823E-03	2.088E-06	35	2	1	2	2	2.888E-04	2.136E-07
18	2	2	2	0	3.137E-04	2.320E-07	36	2	2	2	2	3.209E-05	2.373E-08

5.4 *Results of the risk assessment*

Figure 5 shows the LSIR results for the case-study analysed. It is worth to remind that in all the risk figures reported, the baseline contribution of conventional scenarios is included (i.e., case 0, as explained in Section 4.1). Figure 5-a shows the baseline Natech LSIR from tank T01 (i.e., case 1). Figure 5-d shows the overall LSIR obtained applying the methodology developed in Section 2 (i.e., case 4), while Figure 5-b and Figure 5-c represent the worst-case and the best-case considering escalation caused by domino effect (i.e., case 2 and case 3 respectively, see Section 3).

Comparing Figure 5-a and Figure 5-c, it is clear that including the contribution of escalation scenarios caused by domino effect considering mitigation due to safety barriers with baseline performance produces a limited increase in the LSIR value. However, the risk caused by escalation scenarios increases dramatically when considering the degradation of safety barriers due to the flooding (Figure 5-d). Indeed, in the latter case, the tank farm area is entirely exposed to LSIR values higher that 10^{-5} y^{-1}, while this value is present only in a limited area of the layout in Figure 5-c. Thus, the LSIR is clearly underestimated if the possible barrier degradation caused by natural events is overlooked when assessing Natech scenarios. Nevertheless, comparing Figure 5-d and Figure 5-b (where no barriers are considered), it is clear that the residual barrier performance still contributes to reduce the risk level, since in case of completely unmitigated escalation the tank farm area is exposed to LSIR values as high as 10^{-4} y^{-1}, an order of magnitude higher than in the case of mitigated escalation with degraded barriers.

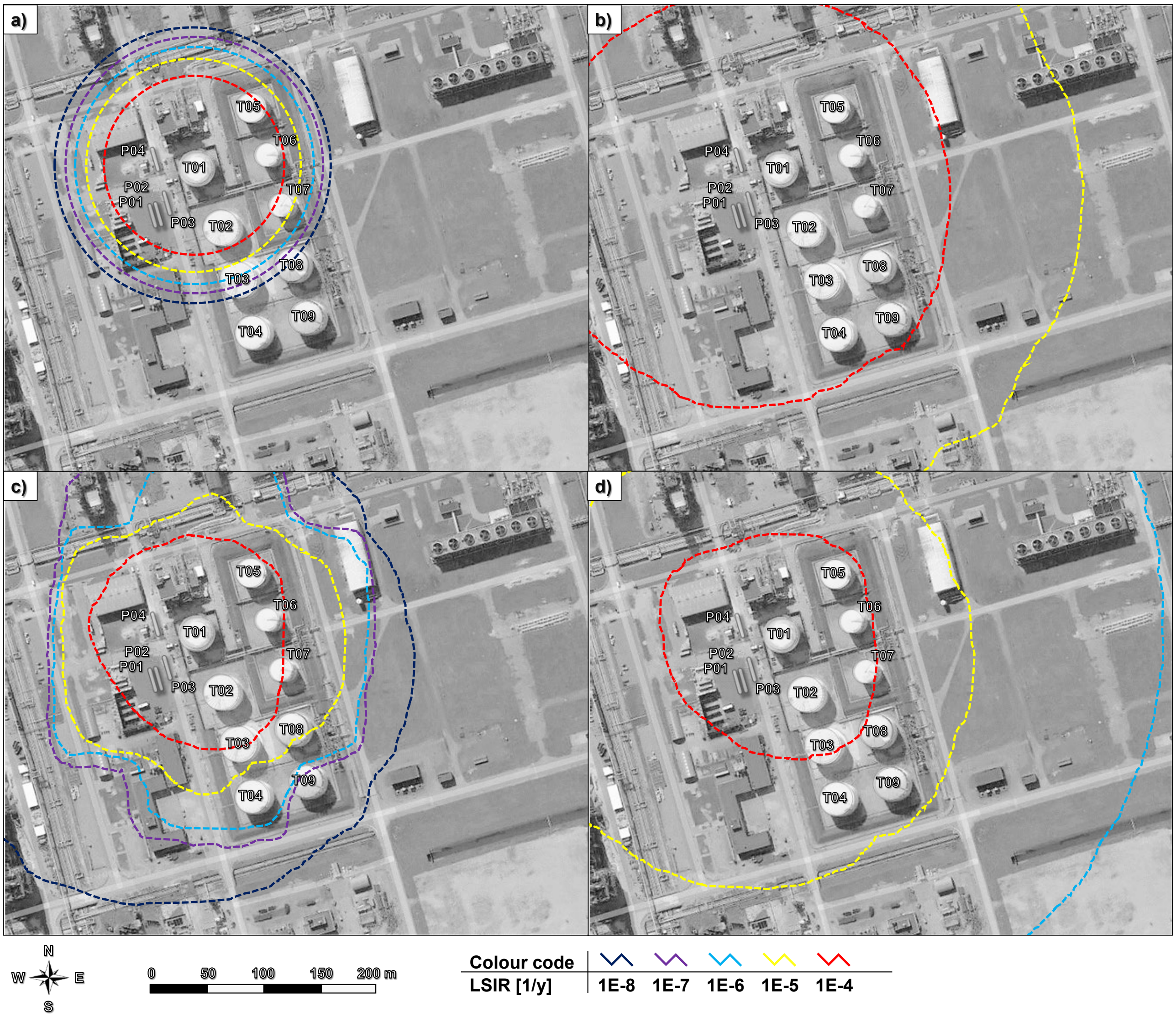

Figure 5: LSIR values calculated for: a) case 1, b) case 2, c) case 3, d) case 4.

Figure 6 describes the societal risk calculated for the four cases considered, obtained considering the simplifying assumptions discussed in Section 4. The severity of the primary Natech scenario (i.e., case 1) is limited (up to 100 expected fatalities). Escalation scenarios have a higher magnitude (up to 1000 expected fatalities), as shown in Figure 6. As expected, the F/N curve of case 4 has an intermediate severity (between that of case 2 and 3), highlighting, on the one hand, that considering unmitigated escalation would be possibly over-conservative, and, on the other hand, that overlooking barrier degradation would lead to a critical underestimation of risk.

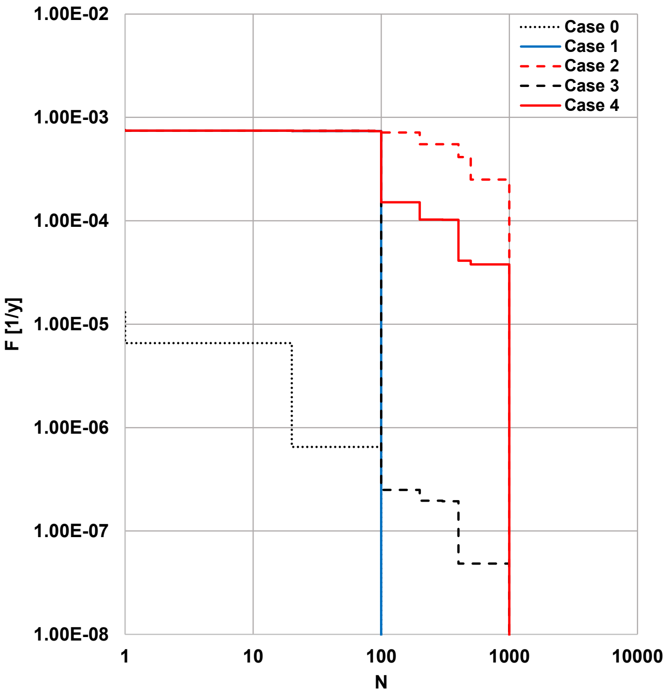

Figure 6: F/N curves calculated for the case-study. Case 0 is reported to provide baseline risk figures related to conventional scenarios.

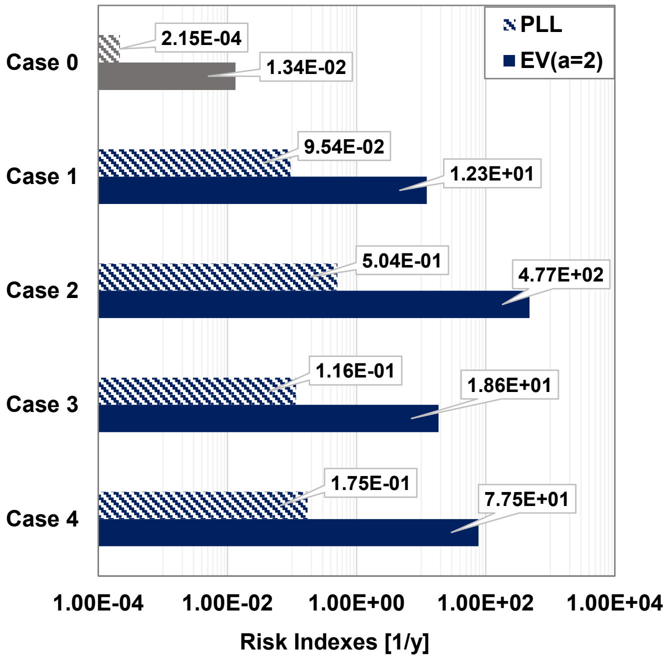

Figure 7: Potential Life Loss (PLL) and expectation value (EV) values calculated for the case study. Case 0 is also reported (in grey) to provide baseline PLL and EV values from conventional scenarios.

The above results are confirmed by the PLL and EV values reported in Figure 7. The values calculated considering the primary Natech accident (i.e., case 1) are about 10^3 times higher than the figures obtained from baseline conventional scenarios (i.e., case 0). Considering escalation caused by domino effect does not affect significantly the PLL, possibly because F and N are equally weighed in the index definition (see Eq. (9)), and the most severe domino scenarios (i.e., scenarios ID 10-36 in Table 8, featuring the rupture of at least one pressurized vessel among P03 and P04) have frequency values considerably lower than that of the primary Natech accident (i.e., 1 to 4 orders of magnitude difference). Thus, the effect of escalation scenarios triggered by Natech is better highlighted by the analysis of the EV index. Indeed, as shown in Figure 7, in case of mitigated escalation considering barrier degradation (i.e., case 4) there is an increase of more than 6 times of the EV with respect to that calculated not considering escalation (i.e., case 1). Adopting baseline barrier performance (i.e., case 3, best-case scenario), the increase is limited to about 1.5 times, while not considering barriers (i.e., case 2, worst-case scenario) the value of EV is about 6 times higher than that of case 4.

5.5 *Discussion*

The results shown in Sections 5.3 and 5.4 allow determining the key role of safety barriers in preventing the escalation of primary Natech accidents by domino effect. Nevertheless, in Natech scenarios, safety barriers might not be as effective as expected in preventing domino effect, due to the impact of natural events that may damage barrier components or impair barrier action. As shown in the case study assessment, the two active firefighting systems considered are found to be not available during a flooding (i.e., the FWS and WDS systems), thus no mitigation will come from the presence of these devices in a Natech scenario triggered by flood. However, the methodology proposed avoids over-conservative results that may be obtained by a worst-case approach that completely neglects the action of all safety barriers. Indeed, passive barriers (e.g., passive fire protection materials) considered in the case study are more robust due to the absence of external activation, and may be considered to resist to the impact of the flooding scenario.

The results obtained show that a relevant increase in the risk indexes is detected when the performance modification of the barriers with respect to baseline values is considered in quantitative risk assessment. The increase in risk figures is not limited to the vicinity of the source of the primary Natech scenario, but rather to the entire facility, involving as well the areas near the equipment items that are potential targets accident. This is clearly related to the high likelihood of high magnitude escalation scenarios and is confirmed by the F/N curves reported in Figure 6, where the contribution of escalation caused by domino effect is mainly related to the presence of specific high impact scenarios. The comparison of the F/N curves for cases 2, 3 and 4 to that obtained for case 1 makes evident this point. Nevertheless, according to the results obtained in the case study, the increase in the risk figures is critical specifically for the scenarios having a higher magnitude. Indeed, the PLL value obtained for the unmitigated case (case 2 in Figure 7) is comparable with the values obtained considering safety barriers (cases 3 and 4 in Figure 7). Differently, the EV parameter, that weights more the scenarios with a higher number of expected fatalities, is about 25 times higher for the unmitigated case (case 2 in Figure 7) with respect to the case considering baseline barrier performance (case 3 in Figure 7), and about 7 times higher than the case considering modifications in barrier performance (case 4 in Figure 7).

Clearly enough, a critical point of the analysis is the selection of the appropriate level of detail for the application of the safety barrier performance degradation analysis. This step is influenced by the available information, in particular on complex barrier systems of interest in the analysis. On the one hand, the selection of L2 level is more information-intensive and is time demanding, although it allows the analyst to take into account specific barrier design provisions (e.g., the application of design standards or solutions explicitly considering natural hazards). On the other hand, if the adoption of L1 and L0 provides sufficiently accurate results and the system may be hardly divided in components, as in the case of simple systems as passive barriers, these levels of analysis provide a straightforward approach to consider performance modification of barriers in risk assessment procedures.

Even if a detailed L2 analysis is applied, uncertainty may still be present in the results, due to the difficulty in assessing the actual behaviour of some components of safety functions when impacted by a natural hazard.

However, the upper and lower risk bounds can be clearly identified by the application of unmitigated domino escalation [46] and mitigated domino escalation considering baseline barrier performance [40] (cases 2 and 3 respectively in the case-study).

The application of the methodology may also be used to drive decision-making in implementing specific provisions for each barrier, with the purpose of shifting the risk level from a situation close to absence of mitigation toward the identified lower risk bound. This approach may be of specific interest considering the L2 analysis, which allows identifying the critical components of the safety barriers that may be considered for upgrading and protection from the impact of the natural event.

Although the multi-level assessment procedure developed for the quantitative assessment of barrier performance modification in Natech scenarios was integrated in a conventional QRA procedure for risk assessment, Steps 4 and 5 may be adopted also in different approaches to quantitative risk assessment. In particular, the quantitative approach to the degradation of barrier performance may be easily integrated with approaches based on Bayesian Networks [33–35] or other graph theoretical approaches [43,44] for the quantitative assessment of the risk of Natech scenarios.

Finally, it should be remarked that the present multilevel approach is not restricted to chemical and process sector and it might be beneficial also in industries where the conceptualization of safety barrier is adopted. For instance, in the nuclear sector, where the system safety is based on defence-in-depth principle [95,96], the methodology might be applied within probabilistic safety assessment (PSA) studies to model explicitly the performance of layers of defence during natural hazards. In doing so, the PSA might drive better risk-informed decisions on how to reduce the likelihood and the impact of accidents originated by natural hazards [97], which, as Fukushima Dai-ichi nuclear disaster (2011) recently demonstrated [6,93,98], safety management might not be ready to face.

6. Conclusions

A comprehensive methodology for the risk assessment of the escalation of Natech scenarios caused by domino effect was developed. The methodology was specifically conceived to allow considering the performance modification of safety barriers during Natech scenarios, caused by the impact of the natural event. A three-level approach was proposed to assess barrier performance modification. The methodology was applied to a case study, and the results obtained are compared with the outcomes of reference methodologies for risk assessment of escalation scenarios caused by domino effect. Risk figures obtained including the modification in barrier performance are of an order of magnitude higher than those obtained considering baseline barrier performance. Still, in particular in the case of high-severity scenarios, even when impacted by a natural event, the layers of protection provided by the safety barriers are effective in reducing of about an order of magnitude the risk with respect to a worst-case scenario where safety barriers are considered absent. The methodology also provides a guidance to the identification of the most critical components of technical safety barriers, supporting risk-based decision-making concerning the upgrading of these systems to improve their resistance to natural events.

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Appendix A

The main assumptions considered for the reference architectures of FWS and WDS in conducting the FTA are reported in Section A.1. The FTA for the WDS, along with the further details on the related application of the L2 level of the proposed methodology (L2 - Step 5c in Figure 1) are reported in Section A.2.

A.1 Assumptions on FWS and WDS architectures

The FTA shown in Figure 3 is based on a reference FWS equipped on tanks T02 and T05 and featuring the following barrier system architecture. A single foam module is conservatively considered, not accounting for the possible presence of redundancies. An in-line eductor system is considered for realizing the intended foam-water mixture [99]. The foam solution is stored in a permanent foam supply tank. The water supply is provided by a permanent firewater tank located inside plant premises which is connected to water main network from the closest inhabited area. The foam/water delivery is accomplished by means of a single fire diesel pump, or by two electric pumps with half nominal capacity compared to the former. Two jockey pumps are considered to maintain the water network to the required pressure balancing small pressure drops due to possible leaks over time [94]. Electric power can be provided from three independent supplies: main power connection, backup supply and diesel generator.

The main features of the reference WDS implemented for protection of vessels P03 and P04 which have been considered in the FTA (see Figure A.1) are reported in the following. The water supply is provided by a permanent firewater tank located inside plant premises which is connected to water main network from the closest inhabited area. The water delivery is accomplished by means of a single fire diesel pump, with a single deluge unit. System actuation can be either automatic or manual from fire area. The electrical actuation system is composed of one solenoid valve receiving electric signal from the control panel receiving fire detection signal from heat detectors. Manual actuation can be performed from fire area following the activation of a fire alarm. Electric power can be provided from three independent supplies: main power connection, backup supply and diesel generator. No fail-safe design is conservatively considered.

A.2 FTA of the reference WDS and details on L2 level application

The FTA for the WDS is reported in Figure A.1. The system probability of failure on demand indicated in Figure A.1 is used as baseline performance value PFD_0 (i.e., in absence of natural hazard) reported in Table 3. The input data $q_{p,0}$ for FTA have been retrieved from standard reliability databases and literature sources [67,87–91]. A 5% beta factor is assumed also in the case of WDS to include the contribution of common cause failure in PFD_0 [67].

The fault tree was then examined to determine critical subsystems considering the reference flood scenario. The most vulnerable nodes identified are highlighted in red in the FTA. As for the case of FWS, the main contribution to the unavailability is linked to the lack of electricity. Indeed, during floods main power connection is likely interrupted due to power grid disruption [92], and given the relevant water height (h_w = 2.0m) floodwater is deemed to submerge also diesel generators which are usually located at ground level [8,93]. The diesel pump can be considered submerged as well in case special provisions for positioning the equipment above ground level had not been previously adopted. Manual actuation is deemed not possible as well, since the releasing panel will not actuate the alarm sound in case of lack of power connection (fail-safe design is conservatively not considered in this study as explained above) and the area might not be reached by operators in case of relevant floodwater height. Therefore, by the application of Eqs. (5) and (6), the PFD_f of the WDS is assessed at unitary value and thus the WDS is considered not available during the Natech accident considered in Section 3.

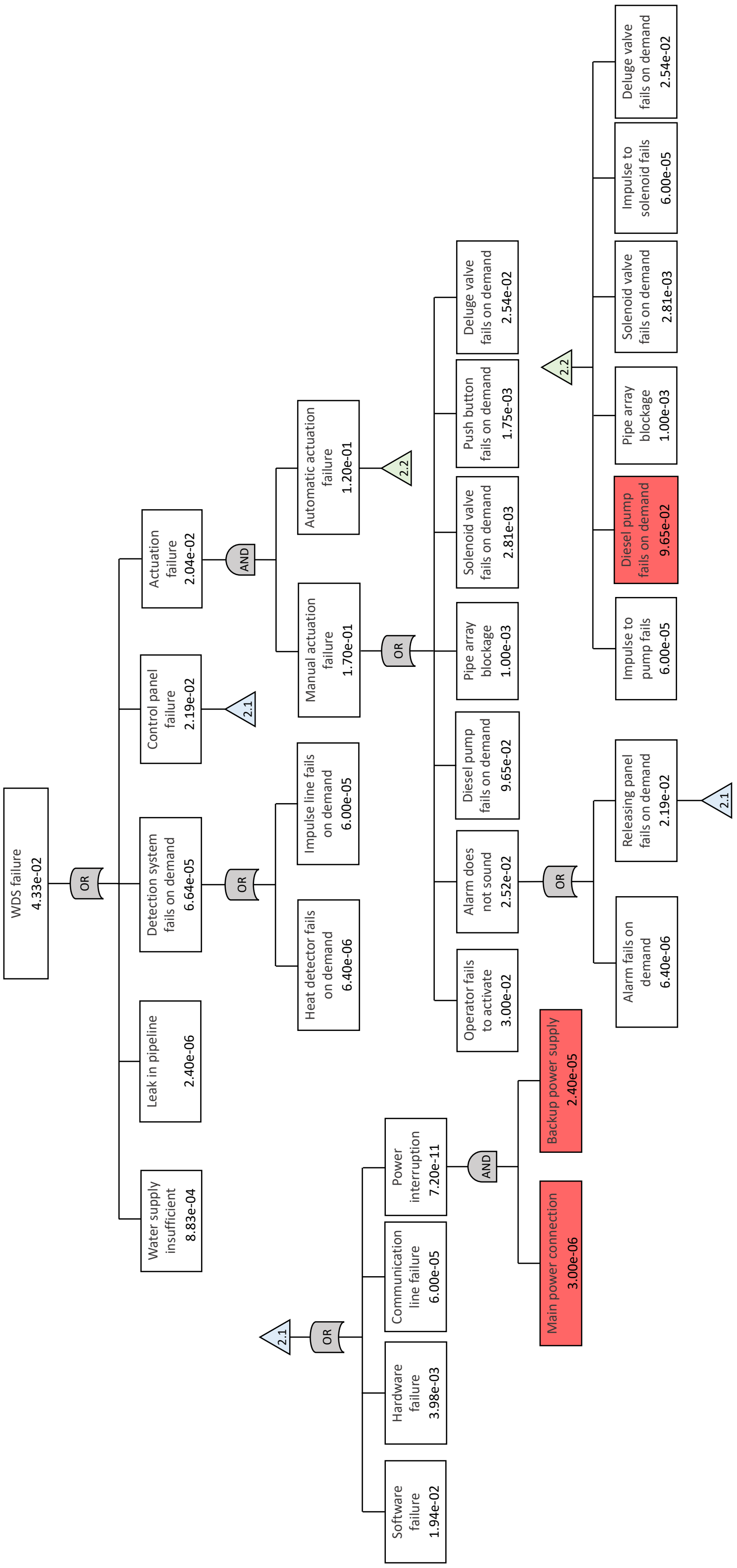

Figure A. 1: Fault tree for the water deluge system (WDS) considered in the case study. Values reported are the baseline unavailability values $q_{p,0}$ which have been used to quantify baseline barrier PFD_0 and updated PFD_f, according to Eqs. (5) and (6). Basic events involving components/subsystems which are deemed not available during the reference flooding scenario are highlighted in red.

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