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Quantitative risk assessment of domino effect in Natech scenarios triggered by lightning

Revised Version

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Abstract

Lightning strike is the natural event more frequency causing Natech accidents involving atmospheric storage tanks. Despite the resulting fires have usually limited severity and only local effects, domino effect may cause the escalation of these primary events, possibly affecting nearby pressurized storages and process equipment, thus resulting in relevant increase in the potential area impacted. A methodology was developed for the quantitative assessment of risk due to domino effects caused by Natech accidents triggered by lightning. A comprehensive procedure was obtained, tailoring lightning risk assessment to include probabilistic models for domino escalation based on probit approach and combinatorial analysis. The methodology was applied to a case-study to evidence the shift in risk figures due to domino effect and the credibility of the secondary domino scenarios. The results of the case-study show that an increase up to two orders of magnitude with respect to risk calculated for conventional scenarios is possible when considering lightning-induced Natech primary scenarios and their escalation.

Keywords

Natech; Domino effect; Escalation; Lightning; Quantitative Risk Assessment; Cascading events.

1. Introduction

Over the last 25 years, the interest of academia and industry toward the investigation of the possible impact of natural hazards (e.g., floods, earthquakes, lightning, hurricanes, etc.) on industrial installations remarkably increased (Showalter and Myers, 1994). Indeed, natural events may trigger severe technological scenarios (the so-called Natech accidents (Krausmann et al., 2016)) when impacting on industrial facilities, in particular when relevant quantities of hazardous materials are stored or processed on the site. Previous studies reported that Natech accidents are about 5% of the records in industrial accident databases (Rasmussen, 1995). Nevertheless, the share of Natech events over the totality of industrial accidents is probably more significant nowadays, and it is expected to further grow as a consequence of climate change (Cruz et al., 2006). Indeed, several publications are suggesting that weather-related phenomena will generally grow in intensity as a consequence of climate change (IPCC, 2018; Peduzzi et al., 2012), becoming high priority risks at global level (World Economic Forum, 2020) and enhancing the threat they pose towards industrial installations and consequently raising the expected frequency of Natech events (Casson Moreno et al., 2019; Necci et al., 2018). For instance, the number of weather-related disasters in the US is sharply grown in recent years (NOAA National Centers for Environmental Information (NCEI), 2018), and the unprecedented features of Hurricane Harvey (2017) were suggested to be in correlation with climate change (Trenberth et al., 2018). Hurricane Harvey is one of the most recent examples of how high impact natural disasters have the potential to trigger Natech accidents and massive chemical releases, mostly due to emergency shutdown operations (Misuri et al., 2019a). International organizations and policy makers are aware of Natech-related emerging risk issues (UNISDR, 2015; WHO, 2018). Regulatory requirements where adopted in the European Union with the last update of the Seveso Directive (European Commission, 2012). Nevertheless, Natech accident features usually go beyond the conventional technological scenarios that companies may expect to face, and an exhaustive quantitative assessment of Natech scenarios is far from simple (Krausmann et al., 2016).

Accident escalation is likely in Natech events, leading to complex and particularly severe overall scenarios (Cozzani et al., 2014). Furthermore, natural hazards are likely to impact also on utilities and safety barriers, possibly increasing the likelihood of accident escalation (Krausmann et al., 2011a; Misuri et al., 2020, 2019b). For instance, the results of a structured expert elicitation on the impact of floods and earthquakes on safety barriers show that probability of failure of safety systems is expected to raise during Natech events (Misuri et al., 2020).

The issue of domino effect in Natech accidents has a particular relevance in the case of lightning-induced Natech events. Actually, several studies evidence that lightning is the natural event most frequently causing Natech accidents (Krausmann et al., 2011b, 2011a; Rasmussen, 1995; Renni et al., 2010). Past accident analysis evidenced that about 95% of Natech accidents triggered by lightning strike took place in the oil&gas (O&G) and petrochemical sectors, and that about 60% of the accidents involved storage tanks (Renni et al., 2010). Since this category of equipment in general is used for storing flammable liquids as crude oil and refined petroleum products, it is not surprising that fire is the most frequent outcome (Argyropoulos et al., 2012; Chang and Lin, 2006).

Indeed, Natech accidents triggered by lightning usually do not have the vast impact area of other natural hazards as floods and earthquakes, due to the limited impact area of a lightning strike (Necci et al., 2014a). However, the fire scenarios following lightning impact on tanks storing flammable chemicals have reportedly constituted a frequent primary cause of domino effect (Persson and Lonnermark, 2004). Table 1 reports some examples of severe accident scenarios started by lightning where escalation due to domino effect played a relevant role in amplifying the overall consequences of the event. As shown in the table, multiple equipment items may be simultaneously involved in such scenario due to domino effects.

In the last two decades, specific frameworks to include the impact of natural hazards in quantitative risk assessment (QRA) were developed for floods (Antonioni et al., 2009a, 2015; Landucci et al., 2012, 2014), earthquakes (Antonioni et al., 2007; Campedel, 2008; Campedel et al., 2008; Fabbrocino et al., 2005; Lanzano et al., 2015, 2014; Salzano et al., 2003) and lightning (Necci et al., 2016, 2014b, 2014a, 2013; Wei et al., 2018). However, on the one hand, the aforementioned studies did not account for the possible escalation induced by Natech accidents affecting neighbouring units. On the other hand, well established methodologies to assess domino effect and domino scenarios in QRA were proposed and validated (Abdolhamidzadeh et al., 2010; Chen et al., 2018; Cozzani et al., 2014, 2006b, 2006a, 2005; Ji et al., 2018; Jiang et al., 2019; Kamil et al., 2019; Khakzad et al., 2016, 2013; Khakzad, 2015; Khakzad and Reniers, 2015; Khan and Abbasi, 1998; Landucci et al., 2017b; Mebarki et al., 2012; Nguyen et al., 2009; Reniers and Cozzani, 2013; Tugnoli et al., 2009). Nevertheless, to date, comprehensive methodologies for the quantitative assessment of risk due to domino effect causing the escalation of Natech accidents are still lacking. A previous specific study only addressed the frequency assessment of domino scenarios triggered by lightning in industrial tank farms (Yang et al., 2018), not considering the analysis of the consequences of the overall scenarios and the calculation of the additional risk deriving from escalation due to domino effect. Thus, available methodologies for quantitative risk assessment of Natech scenarios are not able to capture the contribution to risk deriving from these specific scenarios. Considering the high number of case histories in which severe domino accidents were triggered by lightning, providing a specific methodology for including these scenarios in QRA is of paramount importance, since neglecting such scenarios may lead to an underestimation of the risk.

The aim of the present study is thus to develop a methodology for the comprehensive QRA of domino scenarios caused by the escalation of lightning-triggered Natech events. The description of methodology developed is reported in Section 2. Section 3 reports the description of a case-study defined to demonstrate the effectiveness and potentialities of the methodology, and to exemplify the shift in risk figures and the additional risk deriving from domino effect. The results obtained are presented in Section 4 together with a discussion of the main findings. Lastly, conclusions are presented in Section 5.

Table 1: Examples of domino effects in Natech accidents triggered by lightning.

Date	Location	Description	Reference
09/07/1967	Genoa, Italy	A storage tank ignited during a thunderstorm. Fire spread to other tanks leading to the loss of more than 700 t of oil lost.	(Persson and Lonnermark, 2004)
06/09/1969	Fiumicino, Italy	Lightning bolt cracked the cap of crude oil tank and ignited content. Fire spread to 3 other reservoirs.	(Persson and Lonnermark, 2004)
26/06/1971	Czechowice, Poland	Oil storage was hit by lightning that ignited vapour space. The tank collapsed and vast pool fire involved other 3 tanks. The accident caused 33 fatalities.	(Persson and Lonnermark, 2004)
24/09/1977	Romeoville, Illinois	A lightning struck a fixed roof tank igniting vapour space. The tank exploded and fire spread to nearby tank.	(Persson and Lonnermark, 2004; The French Bureau for Analysis of Industrial Risks and Pollutions (BARPI), 2019)
24/10/1985	(Missing), Louisiana	A lightning ignited the vapour space of a tank that exploded, spreading fire to other 3 tanks nearby.	(Persson and Lonnermark, 2004)
12/08/1989	Quingdao, China	A lightning ignited a 40000 t crude oil tank in an oil terminal. Fire spread to 5 other similar tanks. The accidents caused 16 fatalities and 70 injuries.	(Marsh's Risk Consulting Practice, 2001; Persson and Lonnermark, 2004; The French Bureau for Analysis of Industrial Risks and Pollutions (BARPI), 2019)
21/06/1990	Karkateevy, Russia	A lightning struck a storage tank igniting 5000 t of oil. Resulting fire spread, and other 3 tanks were involved.	(Persson and Lonnermark, 2004; The French Bureau for Analysis of Industrial Risks and Pollutions (BARPI), 2019)
22/07/1994	Delaware City, Delaware	A lightning struck a fuel tank and fire developed. A second tank was involved quickly. 6 firefighters were injured.	(Persson and Lonnermark, 2004)
22/08/1995	Kucove, Albania	Major fire was caused by a lightning strike on a crude oil tank. Followingly, a second crude oil tank nearby exploded. In total, 3 tanks are reported to be involved with a loss of more than 1650 t of crude oil. The accident caused one fatality and four severe injuries.	(Persson and Lonnermark, 2004; The French Bureau for Analysis of Industrial Risks and Pollutions (BARPI), 2019)
24/10/1995	Cilacap, Indonesia	A lightning struck a petroleum product tank, igniting the flammable chemical and leading to roof collapse. Fire spread to 6 other tanks storing naphtha and jet fuel located in the same dike.	(Marsh's Risk Consulting Practice, 2001; Persson and Lonnermark, 2004; The French Bureau for Analysis of Industrial Risks and Pollutions (BARPI), 2019)
10/05/1998	Ras Gharib, Egypt	During a thunderstorm, one of the 16 2000 t oil tanks in an oil terminal was struck by a lightning and set on fire. The fire involved also the other tanks in the terminal.	(Marsh's Risk Consulting Practice, 2001; The French Bureau for Analysis of Industrial Risks and Pollutions (BARPI), 2019)
01/09/2002	Refugio, Texas	A 37 m^3 oil tank was struck by a lightning and caught fire. Flame spread to other 2 tanks and 2 tanker trucks nearby.	(Persson and Lonnermark, 2004)

2. Methodology

2.1 Overview

The procedure to extend the QRA of Natech scenarios induced by lightning to escalation scenarios caused by domino effects is summarized in Figure 1. The methodology stemmed from that developed in previous studies addressing the QRA of Natech events triggered by lightning, where possible escalation was not considered (Necci et al., 2016). The new methodology also shares some features with methodologies proposed for the risk assessment of Natech accidents triggered by floods and earthquakes (Antonioni et al., 2009a, 2015; Cozzani et al., 2014).

As highlighted in a previous publication (Renni et al., 2010), it is unlikely that a single lightning strike can impact simultaneously on more than one equipment item, thus it can be reasonably assumed that only a single unit is damaged by lightning impact, thus causing the primary accident scenario. The possible escalation of the primary event caused by domino effect is then considered, involving the units located nearby.

As shown in figure 1, the procedure developed may be divided in four main parts: i) preliminary data gathering; ii) assessment of primary Natech scenarios; iii) assessment of Natech-induced domino escalation; and iv) overall risk calculation. In the following, the details of each part of the procedure are described in detail.

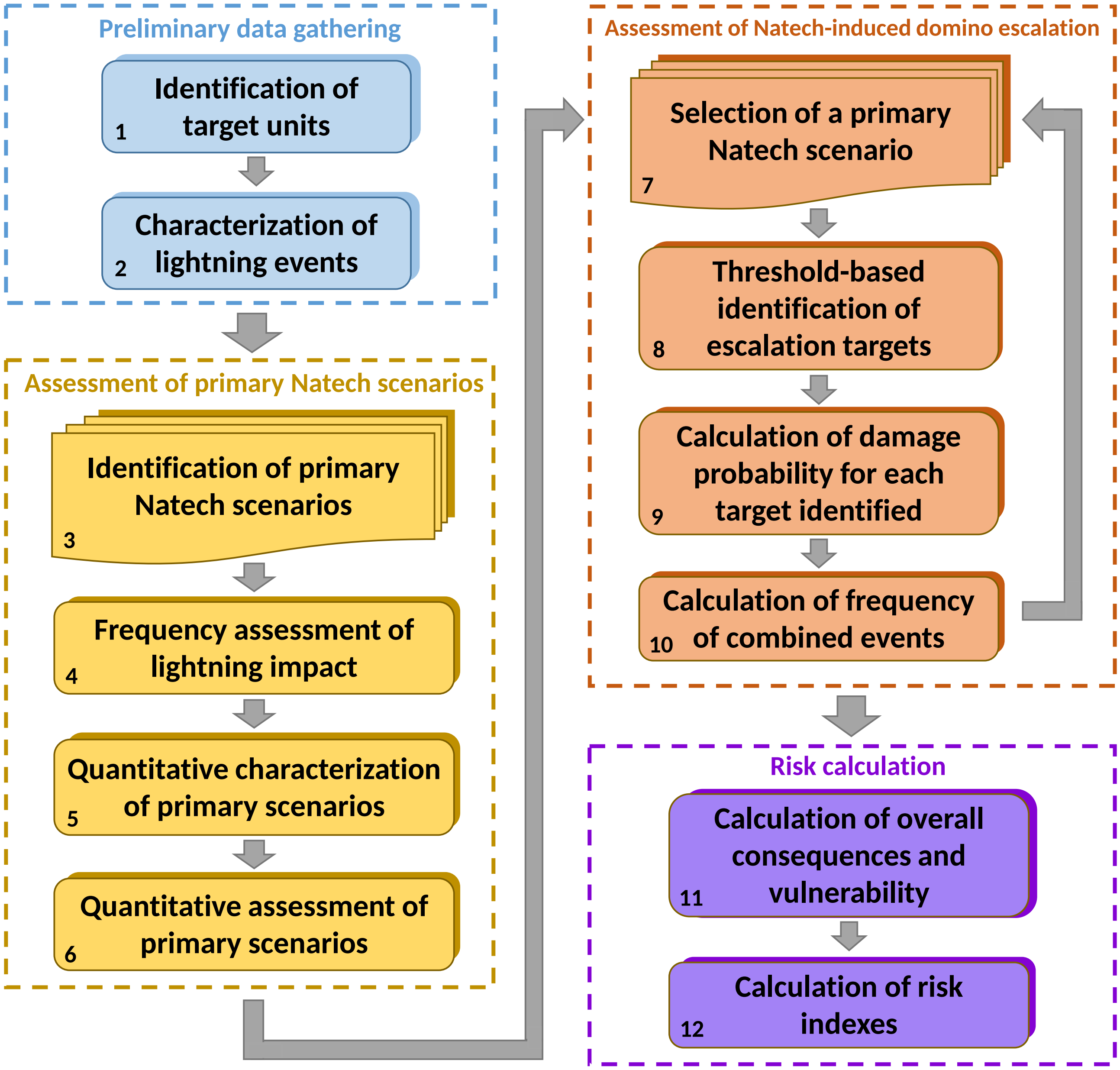

Figure 1: Flowchart of the methodology for risk assessment of lightning-triggered domino-escalated scenarios.

2.2 Preliminary data gathering

The first task of the methodology consists of all the necessary steps to characterize the site under analysis and the lightning hazard insisting on it. As in conventional QRA applications, a limited set of items (yet representative of the layout) should be selected to carry out the analysis, in order to limit its complexity and the required resources. Thus, a preliminary identification of most critical items is needed for prioritization (Step 1 in Figure 1). Semi-quantitative criteria were proposed in the literature to accomplish this aim (Antonioni et al., 2009a). In general, storage tanks should be prioritized, since these equipment items have the highest hold-ups of hazardous substances. Moreover, previous studies on past accident analysis highlighted that the items most frequently involved in Natech events triggered by lightning are atmospheric storage tanks (Renni et al., 2010). On the contrary, pressurized vessels have a limited share in past accidents developing from lightning strike (e.g. in the study from Renni et al. (2010), they are involved only in about 1% of past accident records). This is due both to the more limited sizes of pressurized vessels compared to atmospheric storages, and to the greater shell thickness of these tanks compared to atmospheric storages. Nevertheless, when escalation is addressed, pressurized vessels should be considered as well, since they can be targets of domino effects.

The characterization of the natural hazard insisting on the site of concern is also required. The level of detail of this step should be set with the aim of providing the necessary input data to the risk assessment procedure, rather than to carry out a detailed characterization of the natural hazard. In particular, in case of lightning, data on the expected number or lightning strikes per year in the area of interest is needed, that is the flash density at ground level n_g. Values for this parameter can be retrieved from multiple sources (Aranguren et al., 2017; Enno et al., 2020; IEC, 2015, 2010; Kotroni and Lagouvardos, 2016; LightningMaps.org; Matsui et al., 2019). For instance, the current IEC 62858 international standard specifies criteria to obtain this parameter from lightning location systems (LLS), with the scope of harmonization among measures carried out in difference countries (IEC, 2015). In case field data are not available, a number or correlations based on the number of thunderstorm hours or days for estimating n_g is available (Cigré Working Group, 2013; Huffines and Orville, 1999; IEC, 2010). For instance, for temperate regions, IEC 62305 proposes the following expression to estimate the flash density n_g in flashes/(km^2·year):

$$n_g = 0.1T_d \tag{1}$$

where T_d is the numbers of thunderstorm days per year, which can be obtained from isokeraunic maps (IEC, 2010). Another simplified correlation available was retrieved from the statistical analysis of a significant number of cloud-to-ground flashes registered in U.S. between 1989 and 1996 (Huffines and Orville, 1999). According to this study, n_g can be estimated in US applying the following expression:

$$n_g = 0.024 {T_h}^{1.29} \tag{2}$$

where T_h is the number of thunderstorm hours per year experienced by the site (Huffines and Orville, 1999). In the case study, the work by Kotroni and Lagouvardos (2016) has been used as reference for n_g data.

2.3 Assessment of primary scenarios induced by lightning impact

The impact of lightning on chemical storages may trigger different primary accident scenarios depending on the features of impacted vessel and of the stored substance (Necci et al., 2016, 2014b; Renni et al., 2010). Indeed, lightning strike may cause vessel puncturing, leading to a loss of containment (LOC) event, which in turn can lead to fire in case the released substance is flammable, or to a toxic dispersion if the substance is toxic. Alternatively, lightning impact may ignite flammable vapours present above floating roof tanks starting rim-seal fires, or may cause the ignition of flammable mixtures inside fixed roof tanks (Necci et al., 2014b). Figure 2 shows the event trees (ETs) following lightning impact on different types of storage tanks. It should be noted that cone roof tanks and internal floating roof tanks, in accordance with API 650 and API 2000, may be provided also of a weak joint between roof and lateral courses to allow roof blow-off in case of vapour space ignition and confined explosion, so to prevent vessel catastrophic rupture (API, 2007, 1998).

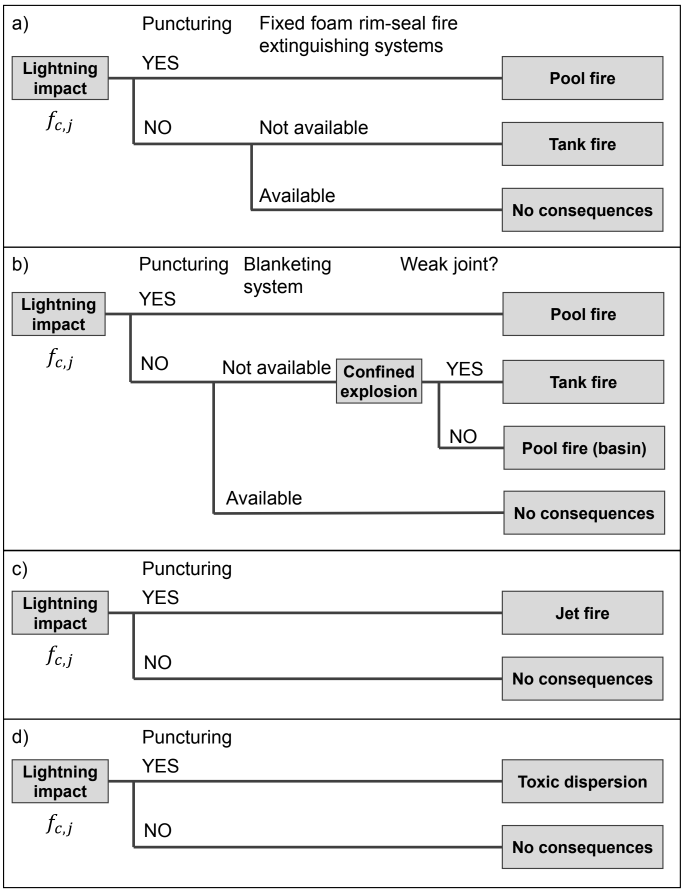

Figure 2: *Event trees (ETs) for accidental scenarios triggered by lightning impact on: a) external floating roof tanks (EFRT) storing flammable substances; b) cone roof tanks (CRT) and internal floating roof tanks (IFRT) storing flammable substances; c) pressurized storage tanks storing flammable substances; d) CRT and pressurized storage tanks storing toxic substances.*

The starting point to estimate the frequencies of the final scenarios (step 4 of the procedure) is the quantification of the lightning impact frequency on each item considered in the study. Lightning capture frequency depends on both the geometrical features of each item and on their spatial distribution, since there is a mutual influence when multiple equipment items are present (Necci et al., 2014a). The IEC 62305 standard (IEC, 2010) reports a complete methodology, which is still based on an equivalent area associated to each equipment and a limited set of location factors defined for some reference situations. These factors are conceptually similar to layout indices (LI) presented in (Necci et al., 2014a). In the present study, a simplified approach derived from the IEC standard and developed by (Necci et al., 2014a) was applied. The methodology allows the calculation of the expected frequency of lightning impact as:

$$f_{c,j} = n_g A_{c,j} \tag{3}$$

where $f_{c,j}$ is the lightning capture yearly frequency on the j-th equipment item and $A_{c,j}$ is the "capture area" of the j-th equipment item, that should be calculated based on its geometrical features and on the lay-out. The approach to the calculation of the capture area is summarized in the supplementary information.

With respect to the features of the final scenarios (step 5 of the procedure), the main issue is related to the puncturing of the shell of the vessel considered. A model based on a statistical distribution of lightning energy was proposed by (Necci et al., 2013), allowing the calculation of the probability of perforation:

$$\ln\left(P_{p,j}\right) = 0.924 - 0.908t \tag{4}$$

where $P_{p,j}$ is the probability of perforation for the j-th item, and t is the shell thickness in mm. When relevant, this expression may be corrected to account for the possibility that the lightning strike hits an area of the vessel that is wetted by the liquid:

$$P_{pp,j} = \frac{P_{p,j} S_{j,L}}{S_{j,tot}} \tag{5}$$

Where $P_{pp,j}$ is the probability that the vessel is perforated below liquid level, S_L is the surface of the tank exposed to liquid, and S_{tot} is the total surface, including the roof. This approach may be also tailored to the case of atmospheric tanks designed with decreasing thickness at increasing height, as it is reported elsewhere (Necci et al., 2016).

The expected size of the hole formed may also be estimated by the model of Necci et al. (2013):

$$D_{h,av,j} = 8.5 * 10^{-3} t^2 - 6.6 * 10^{-3} t + 5.23 \tag{6}$$

where $D_{h,av,j}$ is the average equivalent diameter of the release expressed in mm.

As shown in Figure 2, confined explosion and rim seal fire scenarios should be considered for specific categories of tanks. When relevant, the approach developed by Necci et al. (2014b) may be applied to assess the probabilities of such scenarios.

Frequency assessment of the primary scenarios shown in the event trees reported in Figure 2 (step 6 in the procedure) may be calculated multiplying the frequency of lightning impact by the conditional probability of the scenarios obtained from event tree analysis carried out by the approach discussed above. Consequence analysis of the primary scenarios can be carried out by conventional models for consequence analysis to determine the physical effects (i.e., heat radiation or toxic concentration) (CCPS - Center of Chemical Process Safety, 2000; Mannan, 2005; Van Den Bosh and Weterings, 2005).

2.4 Assessment of escalation caused by Natech primary scenarios

This part of the procedure (steps 7 to 10) should be carried out for each primary scenario identified in section 2.3 (steps 3 to 6). For each of the primary scenarios assessed in step 6, the escalation vectors should be identified (Reniers and Cozzani, 2013). As evident from Figure 2, most of the primary scenarios are stationary fires, and heat radiation is the associated escalation vector. Toxic dispersions are not considered credible sources of escalation (Reniers and Cozzani, 2013). In the case of confined explosion in roof tanks or internal floating roof tanks, fragment projection should also be considered as a possible escalation vector.

A threshold-based approach may then be applied to identify the possible escalation targets, thus restricting the number of possible secondary scenarios (step 8 in Figure 1). A number of threshold values suitable to carry out this step of the analysis are proposed in the technical literature (see (Cozzani et al., 2006b, 2013) and references cited therein). If fragment projection has to be considered, due to the huge potential projection distances, either this step should be skipped considering all targets relevant for escalation, or probabilistic thresholds should be considered, as proposed by Cozzani et al. (2006b).

In step 9 of the procedure, the probability of failure of each possible target identified in the previous step should be assessed. If escalation due to heat radiation is considered, the equipment time to failure (ttf) may be calculated, and the probability of escalation may be assessed comparing the time to failure to the time required for a successful mitigation of the primary event (Landucci et al., 2013). Among the different approaches proposed in the literature for the evaluation of equipment response to fire (Abdolhamidzadeh et al., 2010; D'Aulisa et al., 2014; Ding et al., 2019; Jia et al., 2017; Landucci et al., 2009; Reniers and Cozzani, 2013; Zeng et al., 2020; Zhou and Reniers, 2018), that of Landucci et al. (2009) was applied to the case-study. The specific correlations used to calculate the *ttf* and probability of failure are summarized in the supplementary information.

If fragment projection should be considered, the probability that a fragment impacts the target of interest and the probability of damage of the target should be assessed. Several approaches are available in the literature to this purpose (Mébarki et al. 2009a, 2009b; Gubinelli and Cozzani, 2009a, 2009b; Tugnoli et al., 2014; Sun et al., 2016).

Once the damage probability of each target is assessed, the possibility that multiple simultaneous scenarios originate from the primary fire should be assessed (step 10). A procedure based on combinatorial analysis of simple domino scenarios may be applied (Cozzani et al., 2006a, 2014; Reniers and Cozzani, 2013). Considering all the possible secondary events developing from a primary Natech scenario, an escalation scenario is defined as an event involving the contemporary damage of k out of the n possible targets identified in step 8. The number of escalation scenarios involving k different final outcomes can thus be found according to Eq. (7):

$$N_k = \binom{k}{n} = \frac{n!}{(n-k)!k!} \tag{7}$$

The probability of each overall escalation scenario may be calculated as:

$$P_E^{(k,m)} = \prod_{l=1}^{n}\left[1 - P_{D,l} + \delta(l,\mathbf{J}_m^k)(2P_{D,l} - 1)\right] \tag{8}$$

where $P_E^{(k,m)}$ is the probability of the escalation scenario involving simultaneously k targets units, $\mathbf{J}_m^k$ is a scenario identification vector, whose elements $\gamma_j (j = 1, ..., k)$ are the indexes of the k secondary events that take place during the overall escalation scenario, m indicates that the overall escalation scenario is the *m-th* ($m = 1, ..., N_k$) combination of k secondary events, $\delta(l, \mathbf{J}_m^k)$ is equal to 1 if the *l-th* secondary event belongs to the vector $\mathbf{J}_m^k$, 0 if not, and $P_{D,l}$ is the failure probability of the *l-th* target calculated according to the models adopted in step 9.

The frequency of the *m-th* overall escalation scenario originated from a single primary Natech scenario and simultaneously involving k secondary targets, $f_E^{(k,m)}$, may thus be calculated as:

$$f_E^{(k,m)} = f_{P,Natech} P_E^{(k,m)} \tag{9}$$

where $f_{P,Natech}$ is the frequency of the primary Natech scenario. Based on the results of past accident analysis, primary Natech scenarios are considered mutually independent and simultaneous primary events are not considered (Necci et al., 2016). It is worth noting that the above procedure can be recursively extended to further level domino scenarios, as reported in the literature (Cozzani et al., 2014).

2.5 Risk calculation

Once the frequency of each possible escalation scenario is determined, the consequences should be assessed (step 11 in Figure 1). Conventional models for consequence analysis cannot be applied to the overall scenario, since multiple sources of physical effects (that may be different, as heat radiation and toxic concentration) have to be considered. To this purpose, a methodology based on the calculation of a map of death probability for the overall escalation scenario as the sum of the death probability maps of the primary Natech event and of all the secondary events involved in the overall scenarios, with an upper limit of 1:

$$V_D^{(k,m)} = \min\,[(V_p + \sum_{l=1}^{m} V_{D,l}), 1] \tag{10}$$

where V_p is the death probability at a given position due to the primary Natech event and $V_{D,l}$ is the death probability of the l-th event involved in the $\mathbf{J}_m^k$ escalation scenario of concern. The methodology was derived from that developed for the QRA of domino scenarios in previous studies (Antonioni et al., 2007, 2009b, 2009a, 2015; Cozzani et al., 2005, 2006a, 2014). The maps of death probability related to each primary or secondary event can be determined applying human vulnerability (probit) models to the values of the physical effects obtained from consequence analysis (CCPS - Center of Chemical Process Safety, 2000; Mannan, 2005; Uijt de Haag and Ale, 2005; Van Den Bosh, 1992).

Lastly, individual risk and societal risk can be calculated (step 12 in Figure 1) through standard procedures (CCPS - Center of Chemical Process Safety, 2000; Mannan, 2005; Uijt de Haag and Ale, 2005). Two further risk indices were calculated in the present approach to represent and discuss risk trends: the Potential Life Loss (PLL) and the Expectation Value (EV) (Carter and Hirst, 2000; Hirst and Carter, 2002; Landucci et al., 2017b), calculated as follows:

$$PLL = \sum_N f(N)N = \sum_N F(N) \tag{11}$$

$$EV = \sum_N f(N)N^a \; with \; a > 1 \tag{12}$$

where $f(N)$ is the overall frequency of scenarios causing N expected fatalities, and $F(N)$ is the cumulative frequency of scenarios causing N or more expected fatalities. These indices may be used as useful outcomes for decision making. The main difference between the two indicators is that the EV associates more severe social perception to higher magnitude scenarios. This is accomplished through the application of the parameter ‘a’. Many values have been proposed in the literature for ‘a’: Carter and Hirst propose a value of 1.4 (Carter and Hirst, 2000; Hirst and Carter, 2002), while according to other studies it is possible to find in the literature also values of ‘a’ up to 3 (Okrent et al., 1981). In the case-study presented in the following, the value of 2 has been selected for this parameter, since this value was been used in previous studies on QRA of domino effect (Landucci et al., 2017b).

3. Case study

3.1 Definition of case study

In order to exemplify the results of the proposed methodology, this was applied to a simplified case study, supposedly located in Italy. A fictitious lay-out, derived from that of an existing plant, was considered. The layout, shown in Figure 3, is composed of six atmospheric tanks storing gasoline (T1-T6 in Figure 3), three pressurized horizontal vessels storing GPL (P2-P4 in Figure 3) and one pressurized horizontal vessel storing ammonia (P1 in Figure 3). The main features of the equipment items are summarized in Table 2.

It should be recalled that different event trees are associated to different tank categories, as explained in Section 2. Both external floating roof tanks (EFRT) and cone roof tanks (CRT) are present in the layout. Moreover, among CRTs, tanks T5 and T6 are supposed to be without the weak-joint connection between roof, and T5 is also supposed not to have circumferential tiles.

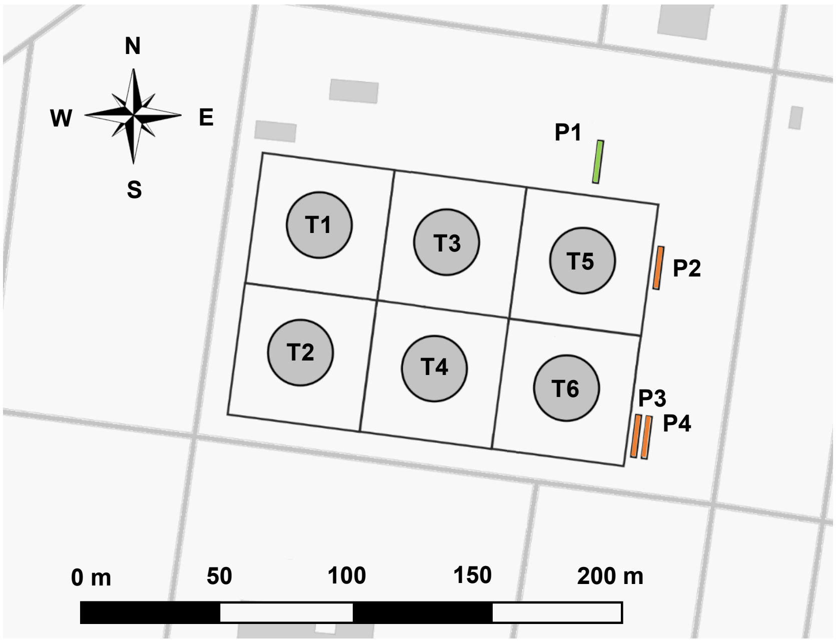

Figure 3: Simplified layout considered in the case study.

Table 2: Description of equipment items considered in the case study (EFRT: external floating roof tank; CRT: conic roof tank; LPG: liquefied petroleum gas).

Vessel or group	**T1-T4**	**T5**	**T6**	**P1**	**P2-P4**
Type	Atmospheric Tank (EFRT)	Atmospheric Tank (CRT; no weak joint)	Atmospheric Tank (CRT; weak joint)	Pressurized vessel	Pressurized vessel
Nominal volume [m3]	6511	6511	6511	150	110
Diameter [m]	24	24	24	3.2	2.75
Length[a] / Height[b] [m]	14.4	14.4	14.4	19.4	19.2
Shell Thickness [mm]	12.5	12.5	12.5	27	24
Filling level	75%	75%	75%	90%	90%
Substance	Gasoline	Gasoline	Gasoline	Ammonia	LPG[c]
Physical state	Liquid	Liquid	Liquid	Liquefied gas	Liquefied gas
Operting pressure [bar]	1.00	1.05[d]	1.05[d]	8.5	2
Inventory [ton]	3656	3656	3656	84	55

a: horizontal vessels (P1-P4), b: vertical vessels (T1-T6), c: pure butane (assumed), d: considering pure nitrogen as blanketing inert gas.

Each atmospheric tank is supposed to be equipped with fire protection systems to reduce the probability and the consequences of fires in case of lightning strike (Necci et al., 2014b). The systems considered for each equipment item together with the associated probability of failure on demand (PFD) are listed in Table 3. The reference values suggested by (Necci et al., 2016) were assumed for the PFD of the fire protection systems considered.

Table 3: Fire protection systems and probability of failure on demand (PFD) considered for atmospheric tanks (EFRT: external floating roof tank; CRT: conic roof tank).

Tank	Type	Fixed foam rim-seal fire extinguishers	Inert gas blanketing system	Weak joint	PFD [1/y]
T1	EFRT	X	-	-	8.1E-3
T2	EFRT	X	-	-	8.1E-3
T3	EFRT	X	-	-	8.1E-3
T4	EFRT	X	-	-	8.1E-3
T5	CRT	-	X	-	5.0E-3
T6	CRT	-	X	X	5.0E-3

In QRA calculations, meteorological data are needed, to be used in physical effect models for consequence assessment (Van Den Bosh and Weterings, 2005). In the case-study, for the sake of simplicity, a single weather class was considered, representative of storm conditions which may be likely associated to lightning strike (Rupke, 2002), characterized by 5m/s average wind speed with uniform distribution and stability class D. Atmospheric temperature of 20°C and relative humidity of 70% were assumed in consequence analysis.

3.2 Conventional scenarios

In order to have a baseline for the risk due to major accidents associated to the layout, a QRA was carried out considering only conventional scenarios (thus excluding both Natech and escalation scenarios). In Table 4 the conventional scenarios included in the analysis are summarized, together with their expected frequencies. Top event frequencies were retrieved from the "Purple Book" (Uijt de Haag and Ale, 2005), while consequence assessment was performed adopting well-established literature models (CCPS - Center of Chemical Process Safety, 2000; Mannan, 2005; Van Den Bosh and Weterings, 2005). Risk figures were calculated by the ARIPAR methodology (Egidi et al., 1995). Probit models used to assess death probability associated to conventional scenarios are reported in

Table 5. For the sake of simplicity, a uniform population density was assumed (200 persons/ha with 60% presence probability).

Table 4: Conventional scenarios considered to assess baseline risk in the case-study (VCE: vapour cloud explosion).

Item(s)	**LOC**	$f_{LOC}\,[1/y]$	P_{ign}	$P_{ign}^{delayed}$	$\frac{P_{flash\,fire}}{P_{VCE}}$	**Scenario**	**Expected frequency** $[1/y]$
T1-T6	Catastrophic rupture	$5.00 * 10^{-6}$	0.065	0.90	$\frac{0.3}{0.7}$	Pool fire (catch basin)	$3.25 * 10^{-7}$
						Flash fire	$1.26 * 10^{-6}$
						VCE	$2.95 * 10^{-6}$
	Continuous release in 10 min	$5.00 * 10^{-6}$	0.065	0.90	$\frac{0.3}{0.7}$	Pool fire (catch basin)	$3.25 * 10^{-7}$
						Flash fire	$1.26 * 10^{-6}$
						VCE	$2.95 * 10^{-6}$
	Leak from 10mm hole	$1.00 * 10^{-4}$	0.065	-	-	Pool fire	$6.50 * 10^{-6}$
P1	Catastrophic rupture	$5.00 * 10^{-7}$	-	-	-	Toxic dispersion	$5.00 * 10^{-7}$
	Continuous release in 10 min	$5.00 * 10^{-7}$	-	-	-	Toxic dispersion	$5.00 * 10^{-7}$
	Leak from 10mm hole	$1.00 * 10^{-5}$	-	-	-	Toxic dispersion	$1.00 * 10^{-5}$
P2-P4	Catastrophic rupture	$5.00 * 10^{-7}$	0.70	0.90	$\frac{0.3}{0.7}$	Fireball	$3.50 * 10^{-7}$
						Flash fire	$4.05 * 10^{-8}$
						VCE	$9.45 * 10^{-8}$
	Continuous release in 10 min	$5.00 * 10^{-7}$	0.50	0.90	$\frac{0.3}{0.7}$	Jet fire	$2.50 * 10^{-7}$
						Flash fire	$6.75 * 10^{-8}$
						VCE	$1.58 * 10^{-7}$
	Leak from 10mm hole	$1.00 * 10^{-5}$	0.20	-	-	Jet fire	$2.00 * 10^{-6}$

Table 5: Human vulnerability (Probit) models applied in the case-study.

Physical effect	**Human vulnerability model** **P: death probability**	***Notes***
Heat radiation	Probit equation: $Y = -14.9 + 2.56 \ln\left(t_{exp} * I^{\frac{4}{3}}\right)$ Vulnerability: $P = normcdf(Y - 5, \mu = 0, \sigma^2 = 1)$	t_{exp}[s]: exposure time to fire I[kW/m^2]: heat radiation
Overpressure	Threshold-based: $\begin{cases} P = 1 \; if \; P_s \geq 0.3bar \\ P = 0 \; if \; P_s < 0.3bar \end{cases}$	P_s[bar]: peak static overpressure
Toxic dispersion	Probit equation: $Y = k_1 + k_2 \ln\left(C^n * t_{exp}\right)$ Vulnerability: $P = normcdf(Y - 5, \mu = 0, \sigma^2 = 1)$	C[mg/m^3]: toxic concentration Ammonia: $k_1 = -15.6$; $k_2 = 1$; $n = 2$; $t_{exp} = 30$min (Uijt de Haag and Ale, 2005)

4. Results and discussion

4.1 Frequency assessment of domino scenarios

In order to assess the yearly frequency of lightning strike on the equipment items considered, data on flash density at ground for the location under analysis are needed. According to (Cigré Working Group, 2013), typical values of flash density for Europe lay within the range of 0.1-10 flashes/(km^2*year). A value of 5 flashes/(km^2*year) was selected for the case study (Kotroni and Lagouvardos, 2016). Figure 4 shows the values calculated for the capture area associated to each equipment item by the methodology presented in Section 2.3. A specific routine was implemented in the Matlab (R2019b) and the layout was discretized in 250000 cells.

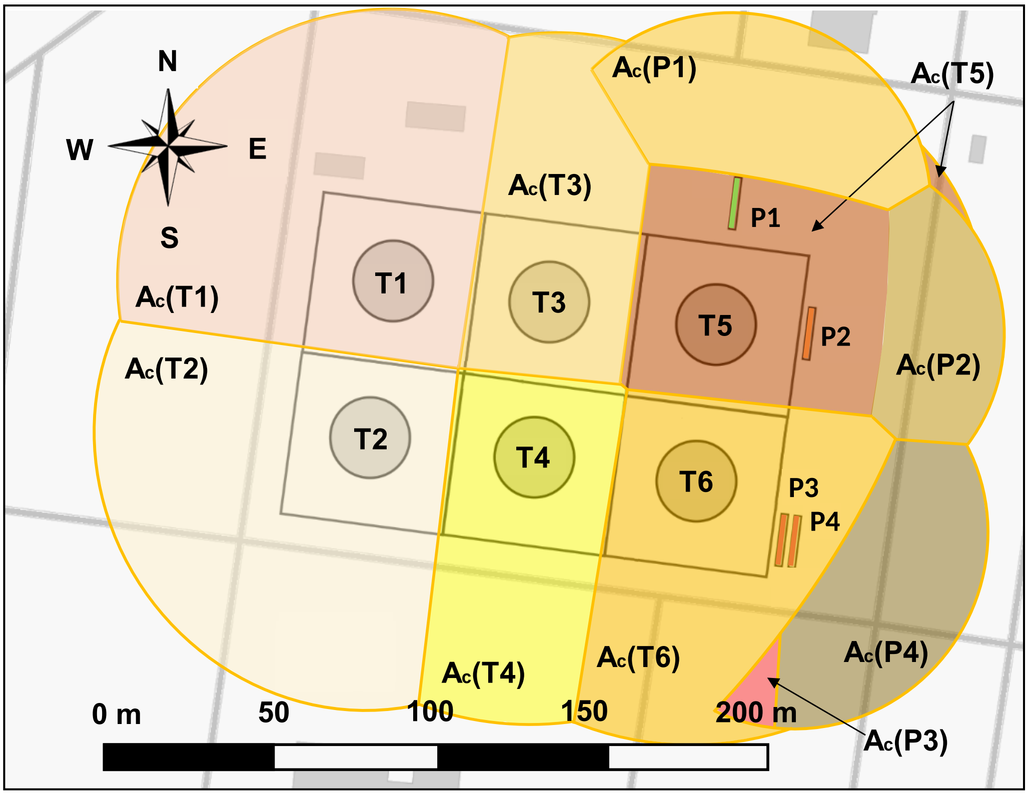

Figure 4: Flash capture area for each item considered.

The calculated values for the capture areas and the corresponding lightning impact frequencies are reported in Table 6. It should be remarked that the quite different values of the LI, confirm the importance of considering the lay-out in the assessment of the lightning impact frequency. Table 6 also reports the probability of vessel shell puncturing for each equipment. The conditional probability of puncturing given the lighting impact is very low, around 10^{-10}, for all pressurized vessels considered, due to the thickness of the shell of these equipment items. As shown in Table 6, the resulting frequencies of primary scenarios involving P1-P4 are very low, below the usual cut-off value of 10^{-10} applied in QRA (Cozzani et al., 2014). Thus, in the case-study, the primary scenarios due to lightning-induced perforation of the shell of horizontal pressurized vessels were not further considered.

Table 6: Lightning capture areas, LI and calculated lightning impact frequencies.

Item	Capture area [m^2]	Layout index (LI)	Lightning impact frequency [1/y]	PP_j Puncturing probability	$D_{h,av,j}$ Average hole diameter [mm]	Direct scenarios	Indirect scenarios	
						Pool Fire /Jet Fire / Toxic dispersion* [1/y]	Tank Fire [1/y]	Catastrophic pool fire (basin) [1/y]
T1	1.0220e+4	0.4561	5.11e-2	1.57e-5	6.5	8.022e-7	4.139e-4	-
T2	1.0436e+4	0.4657	5.22e-2	1.57e-5	6.5	8.192e-7	4.227e-4	-
T3	4.8351e+3	0.2158	2.42e-2	1.57e-5	6.5	3.796e-7	1.958e-4	-
T4	5.2811e+3	0.2357	2.64e-2	1.57e-5	6.5	4.146e-7	2.139e-4	-
T5	5.4667e+3	0.2440	2.73e-2	1.57e-5	6.5	4.291e-7	-	1.367e-4
T6	7.1801e+3	0.3207	3.59e-2	1.57e-5	6.5	5.636e-7	1.795e-4	-
P1	4.2839e+3	0.3633	2.14e-2	5.68e-11	11.2	1.216e-12	-	-
P2	2.3971e+3	0.2151	1.20e-2	8.65e-10	10.0	1.038e-11	-	-
P3	2.6324e+2	0.0236	1.30e-3	8.65e-10	10.0	1.125e-11	-	-
P4	3.6326e+3	0.3258	1.82e-2	8.65e-10	10.0	1.574e-11	-	-

*Pool fire for T1-T6, Toxic dispersion for P1, Jet fire for P2-P4, in agreement with Figure 2.

Table 6 shows the average hole diameter caused by direct shell puncturing, calculated by Eq. (6). Since all the values for tanks T1-T6 resulted lower than 10mm, the smallest LOC diameters suggested for QRA by the “Purple book” guidelines (Uijt de Haag and Ale, 2005), this value was assumed for consequence analysis. The consequence assessment for the primary scenarios was carried out using standard literature models (CCPS - Center of Chemical Process Safety, 2000; Mannan, 2005; Van Den Bosh and Weterings, 2005).

In order to understand which of the Natech primary scenarios analysed could actually cause a domino effect, a preliminary screening was performed, applying step 8 of the suggested procedure. A threshold-based approach was used, assuming the values of 15 kW/m^2 for atmospheric tanks and of 45 kW/m^2 for pressurized vessels (Cozzani et al., 2013). Domino scenarios triggered by fragment projection, only possible for tanks T5 and T6, were not considered to limit the complexity of the case-study, that focuses on the procedure on domino effect assessment, rather than on the detailed investigation of the single scenarios.

Table 7 reports the domino targets identified and the secondary scenarios identified. The table also reports the calculated values of *ttf* and the corresponding domino probability, P_D. The secondary scenarios were identified considering the mechanical failure of the domino target due to heat radiation. Thus, in the case of atmospheric tanks storing flammable substances, a catastrophic pool fire is considered. In the case of pressurized equipment, catastrophic failure was assumed, followed by the formation of a toxic cloud in the case of tank P1 (containing liquefied ammonia), and of a fireball in the case of tank P2 (containing LPG) (Cozzani et al., 2006a).

As discussed in Section 2, the possibility of domino effect affecting simultaneously more than one secondary equipment item should be considered. Table 8 reports the overall escalation scenarios included in the analysis, considering the possible failure of more than one domino target due to the primary scenario. The table also reports the calculated frequencies of the overall escalation scenarios considered.

Table 7: Escalation targets and secondary scenarios considered for each of the primary Natech scenarios analysed (ttf: time to failure; I: heat radiation on the target; P_D: target damage probability given the primary scenario).

Primary item	Primary scenario	Target	Secondary scenario	I [kW/m^2]	ttf [s]	P_D
T1	Tank fire	T2	Catastrophic pool fire	17.3	668	0.417
		T3	Catastrophic pool fire	17.3	668	0.417
T2	Tank fire	T1	Catastrophic pool fire	16.8	691	0.393
		T4	Catastrophic pool fire	15.4	762	0.325
T3	Tank fire	T1	Catastrophic pool fire	16.8	691	0.393
		T4	Catastrophic pool fire	17.5	660	0.426
		T5	Catastrophic pool fire	15.2	774	0.316
T4	Tank fire	T2	Catastrophic pool fire	15.2	774	0.316
		T3	Catastrophic pool fire	17.1	677	0.408
		T6	Catastrophic pool fire	15.2	774	0.316
T5	Catastrophic pool fire (basin)	T3	Catastrophic pool fire	40.2	258	0.940
		T4	Catastrophic pool fire	23.1	482	0.654
		T6	Catastrophic pool fire	43.2	238	0.956
		P1	Toxic dispersion	75.2	533	0.582
		P2	Fireball	75.7	478	0.659
T6	Tank fire	T4	Catastrophic pool fire	15.5	757	0.330
		T5	Catastrophic pool fire	16.9	686	0.398

Table 8: Final escalation scenarios. The equipment item in italic is the source of the primary Natech lightning-induced scenario.

ID	Equipment items	Frequency $[1/y]$	ID	Equipment items	Frequency $[1/y]$
FO01	*T1*	1.41E-04	**FO31**	*T5*, T4, T6	7.32E-07
FO02	*T1*, T2	1.01E-04	**FO32**	*T5*, T3, T4, T6	1.14E-05
FO03	*T1*, T3	1.01E-04	**FO33**	*T5*, P1	2.50E-08
FO04	*T1*, T2, T3	7.20E-05	**FO34**	*T5*, T3, P1	3.91E-07
FO05	*T2*	1.73E-04	**FO35**	*T5*, T4, P1	4.72E-08
FO06	*T2*, T1	1.12E-04	**FO36**	*T5*, T3, T4, P1	7.38E-07
FO07	*T2*, T4	8.35E-05	**FO37**	*T5*, T6, P1	5.41E-07
FO08	*T2*, T1, T4	5.41E-05	**FO38**	*T5*, T3, T6, P1	8.45E-06
FO09	*T3*	4.66E-05	**FO39**	*T5*, T4, T6, P1	1.02E-06
FO10	*T3*, T1	3.02E-05	**FO40**	*T5*, T3, T4, T6, P1	1.59E-05
FO11	*T3*, T4	3.47E-05	**FO41**	*T5*, P2	3.47E-08
FO12	*T3*, T1, T4	2.25E-05	**FO42**	*T5*, T3, P2	5.42E-07
FO13	*T3*, T5	2.15E-05	**FO43**	*T5*, T4, P2	6.54E-08
FO14	*T3*, T1, T5	1.39E-05	**FO44**	*T5*, T3, T4, P2	1.02E-06
FO15	*T3*, T4, T5	1.60E-05	**FO45**	*T5*, T6, P2	7.50E-07
FO16	*T3*, T1, T4, T5	1.04E-05	**FO46**	*T5*, T3, T6, P2	1.17E-05
FO17	*T4*	5.94E-05	**FO47**	*T5*, T4, T6, P2	1.41E-06
FO18	*T4*, T2	2.74E-05	**FO48**	*T5*, T3, T4, T6, P2	2.21E-05
FO19	*T4*, T3	4.08E-05	**FO49**	*T5*, P1, P2	4.84E-08
FO20	*T4*, T2, T3	1.88E-05	**FO50**	*T5*, T3, P1, P2	7.55E-07
FO21	*T4*, T6	2.74E-05	**FO51**	*T5*, T4, P1, P2	9.13E-08
FO22	*T4*, T2, T6	1.26E-05	**FO52**	*T5*, T3, T4, P1, P2	1.43E-06
FO23	*T4*, T3, T6	1.88E-05	**FO53**	*T5*, T6, P1, P2	1.05E-06
FO24	*T4*, T2, T3, T6	8.68E-06	**FO54**	*T5*, T3, T6, P1, P2	1.63E-05
FO25	*T5*	1.80E-08	**FO55**	*T5*, T4, T6, P1, P2	1.97E-06
FO26	*T5*, T3	2.80E-07	**FO56**	*T5*, T3, T4, T6, P1, P2	3.08E-05
FO27	*T5*, T4	3.39E-08	**FO57**	*T6*	7.24E-05
FO28	*T5*, T3, T4	5.29E-07	**FO58**	*T6*, T4	3.57E-05
FO29	*T5*, T6	3.88E-07	**FO59**	*T6*, T5	4.79E-05
FO30	*T5*, T3, T6	6.06E-06	**FO60**	*T6*, T4, T5	2.36E-05

4.2 Quantitative risk assessment of secondary scenarios

The methodology described in section 2.5 was applied to calculate the individual and societal risk for the case-study, based on assumptions discussed in section 3. Figure 5-a) shows the local-specific individual risk (LSIR) contours obtained considering only the conventional accident scenarios. Figure 5-b) shows the LSIR contours calculated considering both the conventional and the primary lightning-induced Natech scenarios, but without considering the possibility of escalation. Figure 5-c) reports the results obtained also considering the overall escalation scenarios. The figure clearly shows the increase in the LSIR values on the lay-out considered. While this effect is rather limited considering primary Natech scenarios only, in case domino effect is accounted significant areas of the layout show individual risk levels up to two orders of magnitude higher, due to both the high frequency of lightning scenarios and to the severity of the possible escalation.

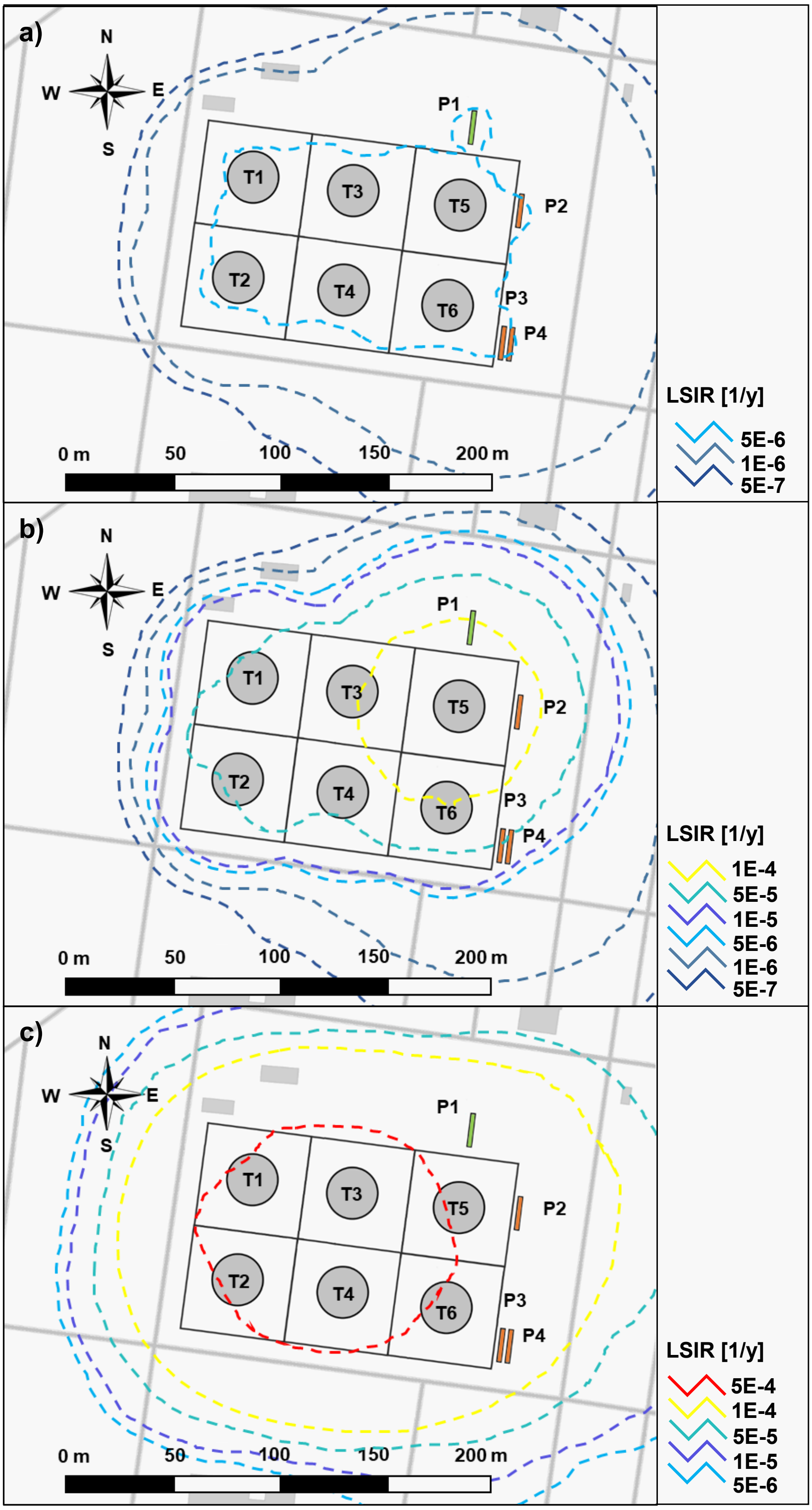

Figure 5: a) Local-Specific Individual Risk (LSIR) contours obtained considering only conventional scenarios; b) LSIR contours obtained considering conventional and primary lightning-induced Natech; c) LSIR contours obtained considering conventional scenarios, primary Natech scenarios and overall escalation scenarios.

Figure 6 shows the societal risk F/N curves calculated for the case-study. Three curves are reported: that for conventional scenarios only (curve labelled with ‘a’ in Figure 6), the one calculated considering conventional and primary lightning-induced Natech scenarios (curve ‘b’ in Figure 6), and the one calculated also considering overall escalation scenarios (curve ‘c’ in Figure 6).

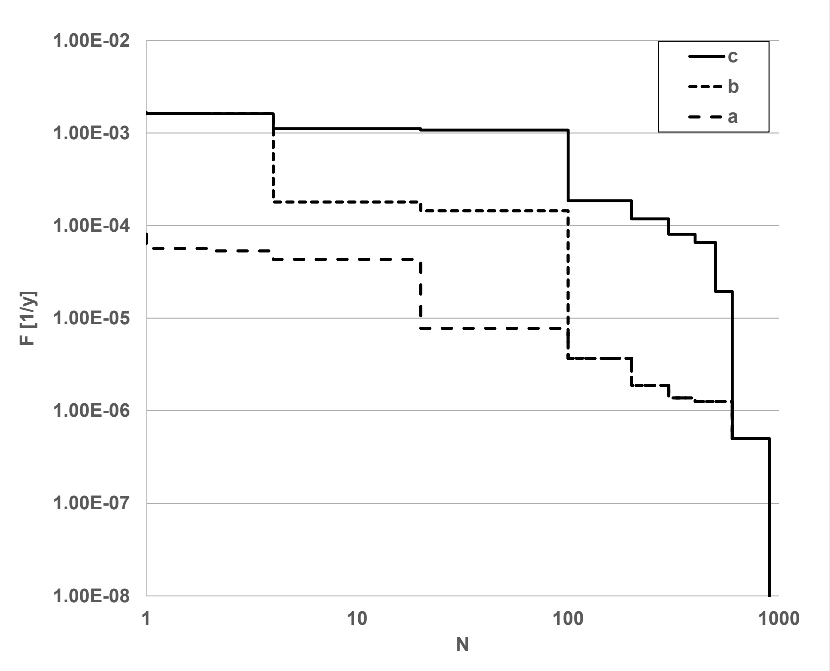

Figure 6: Societal risk associated to the case study, expressed by F/N curves. Curve a: conventional scenarios only; curve b: conventional and primary lightning-induced Natech scenarios only; and curve c: conventional and Natech scenarios including overall escalation scenarios.

The F/N curves show specific differences for the three different cases considered. The F/N curve calculated for the conventional scenarios (curve ‘a’ in Figure 6) shows some low-severity high-frequency steps on the left, mainly due to the pool fire scenarios from atmospheric tanks, while the steps on the right, having a lower frequency and a higher severity, are caused by the scenarios due to pressurized tanks. When conventional and primary lightning-induced Natech scenarios are only considered (curve ‘b’ in the plot), only the right part of curve ‘a’ is modified, with the new scenarios induced by lightning causing a relevant increase in the overall frequencies of such low-severity events. The right part of the curve is not modified, since the frequencies of direct lightning-induced scenarios involving the pressurized tanks considered is negligible. However, when the overall escalation scenarios are also considered (curve ‘c’ in Figure 6), also in the right part of the curve some new steps appear, due to the higher frequency of severe scenarios caused by the escalation of the primary Natech scenarios.

EV and PLL indices are then calculated applying Eq. (11) – (12); the ‘a’ parameter was set to 2 in Eq. (12), as discussed in section 2.5. As shown in Figure 7, when Natech scenarios triggered by lightning are considered, PLL and EV increase of a factor around 8 and 3, respectively. However, in case domino escalation is included in Natech assessment, PLL and EV respectively jump up to more than 68 and 54 times, respectively, the values for conventional scenarios.

As shown in Figure 7, PLL increases of about 8 times when lightning scenarios are considered. If the overall escalation scenarios are also considered, PLL rises of about two order of magnitude with respect to the value calculated for conventional scenarios. The EV index increases of about 3 times when lightning-induced Natech primary scenarios are considered. However, when also the overall escalation scenarios are included in the calculations, its value rises to about 53 times the value calculated for conventional scenarios only.

These results highlight the importance of considering domino effect in the assessment of lightning-induced Natech risk assessment. Actually, previous studies (Necci et al., 2016) reported that lightning-induced Natech scenarios, although having a high frequency, usually result in low severities due to the low credibility of direct lightning damage of pressurized equipment. These results were confirmed by the analysis of the present case-study. However, when considering the possibility of domino effect, such conclusions should be modified. Actually, the escalation of lightning-induced scenarios may cause severe overall scenarios with non-negligible frequencies, as shown by the results of the present case-study. The possibility of domino effects may be even enhanced by the adverse conditions taking place during severe thunderstorms (heavy rain, local flooding, possible interruptions of electric energy supply), since harsh weather conditions may hinder the emergency response and the mitigation actions needed to prevent escalation scenarios (Landucci et al., 2017a).

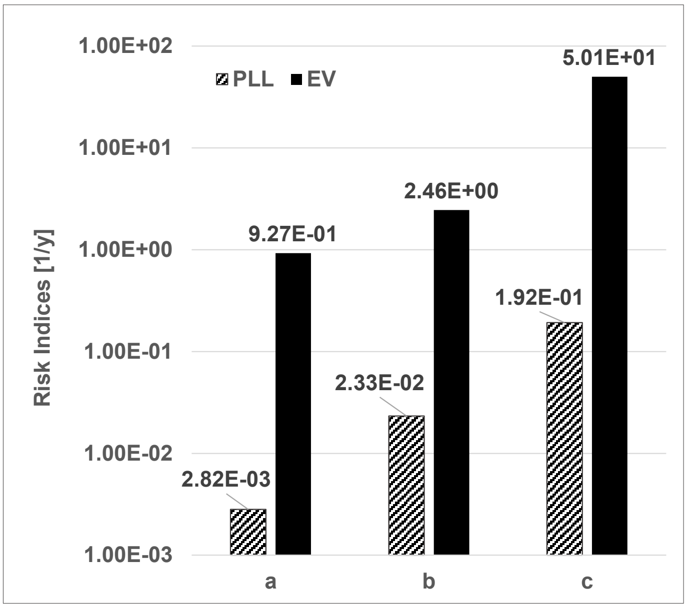

Figure 7: Potential Life Loss (PLL) and expectation value (EV) risk indices calculated for the case study: a) considering only conventional scenarios; b) considering both conventional and primary lightning-induced Natech scenarios; c) considering also overall escalation scenarios.

5. Conclusions

The specific conditions occurring during Natech events may enhance the possibility and probability of escalation of Natech primary scenarios. This has a particular relevance when considering lightning-induced Natech scenarios, since such events, usually having a low severity and only local effects, may trigger domino effects causing a relevant increase in the impacted area and in the severity of the overall scenario. The novel methodology developed in the present study, aiming at the QRA of Natech scenarios accounting for the possibility of escalation caused by domino effect, was able to quantify the shift in risk figures caused by considering Natech scenarios induced by lightning and their possible escalation. The results of a case-study demonstrated that risk indexes may increase of about an order of magnitude when considering primary Natech scenarios induced by lightning, and of about a further order of magnitude when considering the possibility of domino effect. Indeed, considering domino effect significantly increases the frequency of high-severity escalation scenarios triggered by lightning strikes. Thus, the proposed methodology represents a useful tool to support a better risk-informed decision-making process for Natech risk prevention and reduction, and a relevant step towards the assessment of domino effects in the framework of Natech risk assessment.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Alessio Misuri: Conceptualization, Methodology, Software, Writing – original draft

Giacomo Antonioni: Methodology, Software

Valerio Cozzani: Conceptualization, Supervision, Writing – Review