CHEMICAL ENGINEERING TRANSACTIONS

VOL. 91, 2022

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Valerio Cozzani, Bruno Fabiano, Genserik Reniers

ISBN 978-88-95608-89-1; **ISSN** 2283-9216

DOI: 10.3303/CET2291083

Multi-risk Approach to the QRA of Natech Scenarios in the Chemical and Process Industry

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A novel quantitative methodology to perform a multi-risk assessment of technological scenarios triggered by natural hazards (Natech events) is presented. The framework is based on a multi-hazard approach and is proposed to assess the risk associated to the different natural events to which an industrial site where relevant quantities of hazardous substances are present is exposed to. The quantitative methodology allows the calculation of failure frequencies, consequences of the scenarios and risk indexes which are compared and benchmarked. Finally, a case study is defined taking into account the impact of earthquakes, floods and lightning strikes. The application leads to the quantification of the contribution of each reference natural event considered to the overall risk figures. Moreover, the methodology proposed enables the evaluation of the relative weight of the risk related to each natural hazard for the selected facility.

1. Introduction

Natech events are technological accidents involving hazardous materials that can be triggered by the impact of natural events as earthquakes and floods on chemical and process installations. This kind of accidents occurred several times in the past, leading to structural damages of main items, subsequent loss of containment (LOC) of hazardous substances and in some cases to catastrophic consequences, high number of deaths and significant economic losses (Krausmann et al., 2011). Natech accidents according to Rasmussen (1995) characterize up to 5% of the total records reported in industrial accident database. Presumably, this fraction is even higher nowadays and expected to increase since frequencies and intensities of natural calamities are growing also due to climate change (WHO, 2018). Not surprisingly, an increasing trend of Natech events in the last 70 years was observed in recent publications (Ricci et al., 2021).

Natech QRA procedures have been developed following the same steps that characterize conventional QRA, although some specific features were conceived to take into account the characteristics of scenarios triggered by natural events (Misuri and Cozzani, 2021). In particular, some additional steps have been included, that is, the natural event characterization, the use of vulnerability models to assess the likelihood of equipment failure, and the assessment of multiple and simultaneous scenarios (Antonioni et al., 2015).

In this contribution, a novel quantitative methodology to perform a multi-risk assessment of Natech scenarios is presented together with an example of application to a case study. Compared to previous approaches, focused mostly on a single hazard per time, the novel methodology has a twofold advantage. Indeed, on the one hand it enables the quantification of the overall Natech risk related with all the possible natural hazards a site is exposed to. On the other hand, the methodology can be used as a tool to obtain a criticality ranking of natural hazards from the standpoint of their contribution to overall technological risk, providing useful criteria to prioritize risk-mitigation strategies.

2. Methodology

The conceptual framework for the multi-risk assessment methodology is reported in Figure 1. It was based on the established framework to perform Natech QRA developed by Antonioni et al. (2015). Previous Natech QRA

Paper Received: 28 November 2021; Revised: 30 March 2022; Accepted: 15 April 2022
Please cite this article as: Sorichetti R., Misuri A., Di Padova A., Miglionico R., Tallone F., Cozzani V., 2022, Multi-risk Approach to the Qra of Natech Scenarios in the Chemical and Process Industry, Chemical Engineering Transactions, 91, 493-498 DOI:10.3303/CET2291083

approaches consider one or more reference events associated to a single natural hazard while the proposed framework considers all the possible natural hazards a chemical/process plant may be exposed to (e.g., earthquake, flood, lightning strikes, extreme temperature and so on).
Therefore, each identified natural hazard (Step 1) needs to be characterized in terms of severity and frequency at the location of the plant (Step 2). Then, a limited set of critical items should be identified together with associated accident scenarios, by means of criteria based on inventory and physical state of hazardous substances (Step 3). In Step 4 the application of equipment vulnerability models is needed to assess the equipment damage probability. Then, the probability/frequency of the identified accident scenarios are evaluated applying event tree analysis. The consequences of the final outcomes of an accident scenario can be assessed using consequence models available in the literature (Step 5). In the case of some high-impact natural hazards, there is a significant likelihood that several process and storage units are damaged simultaneously, and thus more than one release event can occur at the same time leading to complex Natech overall scenarios. This is considered in Step 6 where the event combinations are identified, and their overall frequencies and consequences evaluated. In Step 7 the risk from the identified accident scenarios is estimated and expressed through individual risk maps and societal risk F/N curves. Note that Step 3 to 7 are common to well established Natech QRA approaches (Antonioni et al., 2015). The overall risk related to the different natural hazards on the plant is then evaluated (Step 8) together with the relative weight related to each single natural hazard (Step 9). Finally, based on the single natural hazard contribution to the overall risk, a ranking of natural hazards leveraging risk-based criteria is provided (Step 10). In the following section a case study is provided in order to show a practical application of the methodology of Figure 1.

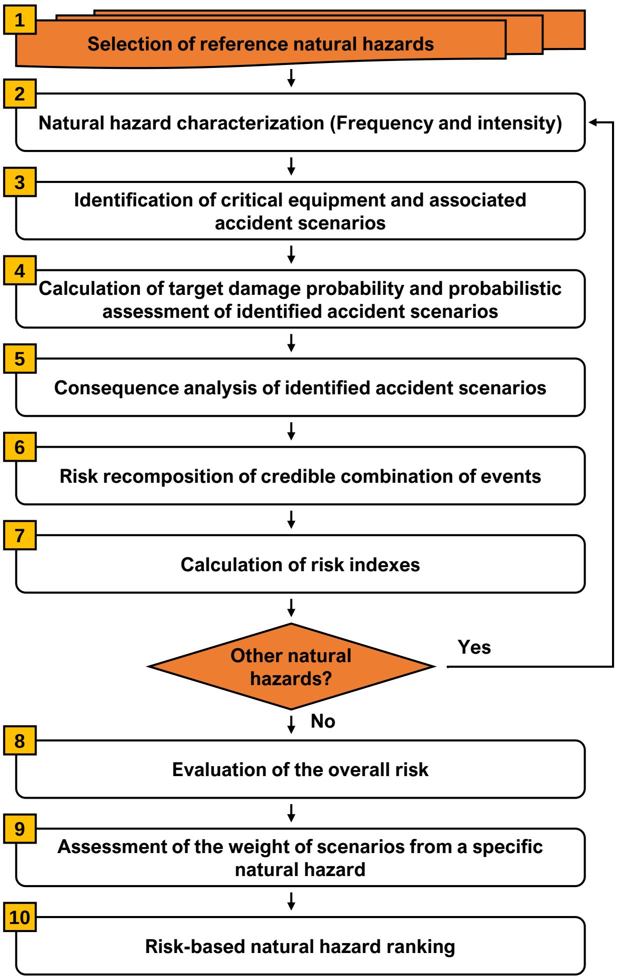

Figure 1: Conceptual framework for multi-risk assessment of technological scenarios triggered by natural hazards.

3. Case study

In order to demonstrate the application of the methodology of Figure 1, a notional case study is developed. The layout is supposedly located in Italy and comprises two atmospheric tanks storing gasoline (A1-A2) and two pressurized horizontal vessels storing propane (P1-P2). The main features of the equipment items are summarized in Table 1.

The site is assumed to be exposed to earthquakes, floods and lightning strikes. The following reference natural events were assumed (Steps 1 and 2 of Figure 1): i) an earthquake with PGA of 0.5g and 500-years return period; ii) a 200-y return-period flood characterized by water height of 2 m and water velocity of 1 m/s; iii) a lightning flash density at ground level of 5 flashes/(km^{2}y). Moreover, to have a baseline for the risk due to major technological accidents associated to the layout, a QRA is performed considering only conventional scenarios as done in previous studies (Misuri et al., 2020). The set of considered conventional scenarios is realized consistently with standardized guidelines for performing the QRA (Uijt de Haag and Ale, 2005).

*Table 1: Main features of the equipment considered. *Average density of the blanketing gas.*

Vessel Features	A1-A2	P1-P2
Type	Atmospheric floating roof	Horizontal pressurized
Nominal capacity [m^3]	13300	102
Diameter [m]	42	2.6
Height/Length [m]	9.6	19.2
Shell thickness [m]	8	18
Vessel tare weight [metric ton]	79	20
Saddle parameter [m]	-	1.5
Filling level	75%	90%
Substance contained	Gasoline	Propane
Physical state	Liquid	Liquefied gas
Pressure [bar]	1.05	8.4
Liquid density [kg/m^3]	740	460
Vapor density [kg/m^3]	0.97*	15.4
Inventory [metric ton]	7380	45

Table 2: Natech scenarios considered in the QRA of the case study (VCE: vapour cloud explosion).

Tank ID	Top Event	Final Outcomes	Frequency (y^{-1})
Earthquake			
A1-A2	Catastrophic rupture	Pool Fire	1.01E-05
		Flash Fire	6.98E-06
		VCE	1.63E-05
P1-P2	10 min release	Jet Fire	1.27E-05
		Flash Fire	8.34E-06
		VCE	1.95E-05
Flood			
A1-A2	Catastrophic rupture	Pool Fire	1.01E-05
		Flash Fire	6.95E-06
		VCE	1.62E-05
P1-P2	10 min release	Jet Fire	1.26E-04
		Flash Fire	8.26E-05
		VCE	1.93E-04
Lightning			
A1	10 mm release	Pool Fire	1.44E-04
	Roof failure	Tank Fire	6.61E-04
A2	10 mm release	Pool Fire	1.46E-04
	Roof failure	Tank Fire	6.67E-04
P1	10 mm release	Jet Fire	9.25E-09
P2	10 mm release	Jet Fire	1.02E-08

Natech scenarios are summarized in Table 2 together with the associated final frequency values (Step 3 and 4). The vulnerabilities of the items to the reference earthquake were evaluated applying specific probit functions

(Salzano et al., 2009). For the case of flood, the vulnerability models proposed by Landucci et al. (2012) were used for atmospheric tanks, and the ones proposed by Landucci et al. (2014) for pressurized vessels. Finally, lightning vulnerability was evaluated following the methodology reported in Misuri et al. (2020). The frequencies of earthquake-induced and flood-induced final scenarios were evaluated applying conventional event tree analysis (ETA) and using ignition probability values available in the literature (Energy Institute, 2019). For Natech scenarios driven by lightning strikes, the specific ETA proposed by Necci et al. (2016) was applied considering the presence of a fixed foam rim-seal fire extinguishing systems for atmospheric tanks A1 and A2, and an immediate ignition probability equal to 1 for all the LOCs, as suggested by Renni et al. (2010). Physical effects for consequence assessment (Step 5) associated to the final outcomes reported in Table 2 were calculated by literature models (Van Den Bosh and Weterings, 2005). The risk recomposition step (Step 6) required when multiple simultaneous LOCs are expected, in this case for the scenarios triggered by the reference flood and earthquake, was based on an established procedure described elsewhere (Antonioni et al., 2015). The individual risk and societal risk figures were evaluated (Step 7) according to standard approaches (CCPS, 2000), enabling the also quantification of the relative contribution of each natural hazard to the overall multi-risk figures. Two additional indices were also adopted to ease result interpretation: the Potential Life Loss (PLL) and the Expectation Value (EV) as done in Misuri et al. (2020).

4. Results and discussions

The risk figures obtained for the case study described in Section 3 are discussed in the following.

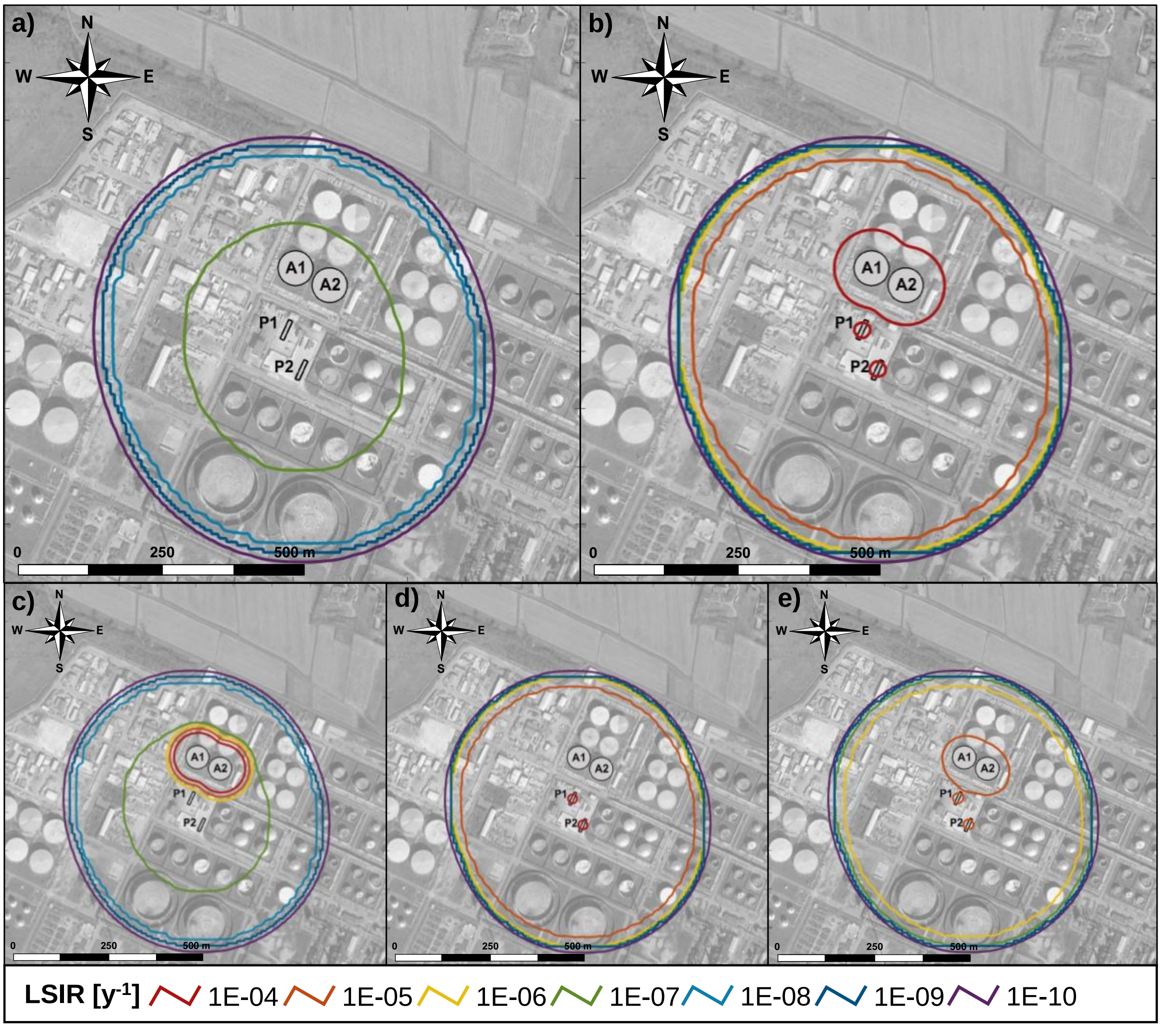

Figure 2: Local-Specific Individual Risk (LSIR) contours obtained considering: a) only conventional scenarios; b) the overall risk; c) conventional and primary lightning-induced Natech; d) conventional and primary flood-induced Natech; e) conventional and primary earthquake-induced Natech.

Figure 2 shows the local-specific individual risk (LSIR) contours obtained considering only the conventional scenarios (panel a), the overall Natech risk (earthquake, lightning and flood contributions, panel b), primary lightning-induced Natech scenarios (panel c), primary flood-induced Natech scenarios (panel d), and primary earthquake-induced Natech scenarios (panel e). The baseline risk contribution of conventional scenarios (panel a) is considered also in all the other panels of Figure 2. The figure clearly shows for each considered natural hazard an increase in the LSIR values, since new areas associated to risk higher than 1E-07 y^{-1} are identified. While this effect is rather limited in the vicinity of the atmospheric tanks A1 and A2 considering primary Natech scenarios induced by lightning strikes (Figure 2b) due to the fact that pressurized items (P1 and P2) are characterized by low values of perforation frequencies, in case of Natech scenarios induced by earthquake and flood (Figure 2b and 2c) significant areas of the layout show individual risk levels up to two orders of magnitude higher compared to panel a, due to both the higher frequency of scenarios involving the pressurized items and to the higher severity of the final outcomes. In particular, flood-induced Natech scenarios lead to the greatest LSIR, and this can be related to the fact that the flood vulnerability models adopted for pressurized items suggested a failure probability equal to 1 resulting in frequencies an order of magnitude higher with respect to those obtained for earthquake-induced scenarios. However, analyzing the obtained overall risk curves (Figure 2b) it can be noticed that flood and lightning scenarios play a major role in risk increase: Natech scenarios caused by floods led to the creation of new risk areas with values between 1E-05 y^{-1} and 1E-04 y^{-1}, with peaks higher than 1E-04 y^{-1} achieved in the proximity of vessels P1-P2, whereas the contribution of lightning-triggered Natech scenarios led to an increase of LSIR to values higher than 1E-04 y^{-1} in the proximity of the atmospheric tanks A1-A2. Even if some suggestions on which natural hazard should be prioritized in risk mitigation strategies, it is not easy to obtain a ranking by the direct analysis of the LSIR curves only, while societal risk figures offer much clearer indications, as shown in Figure 3. Indeed, Figure 3a shows the four societal risk F/N curves calculated for the case study: for conventional scenarios only (black-dashed curve), the one calculated considering conventional and primary lightning-induced Natech scenarios (red curve), while the remaining two are obtained considering also the primary earthquake-induced Natech scenarios (green curve) and finally adding the scenarios triggered by the reference flood (yellow curve, indicating the overall societal risk).
If only the conventional scenarios are considered, the curve shows some low-severity high-frequency steps on the left, mainly associated to the pool fire scenarios from atmospheric tanks, while the lower frequency higher severity steps on the right are caused by the scenarios involving pressurized tanks. Introducing primary Natech scenarios triggered by lightning, a substantial increase in the overall frequencies of low-severity events (left part of the curve) is spotted, while the right part of the curve is not affected (this is due to the low frequency of pressurized equipment failure due to lightning strikes). However, when scenarios induced by earthquake and flood are considered, new steps are created in the right-hand part of the curve due to the higher frequencies of more severe scenarios (e.g., 10 min releases from P1 and P2, followed by flash fires).

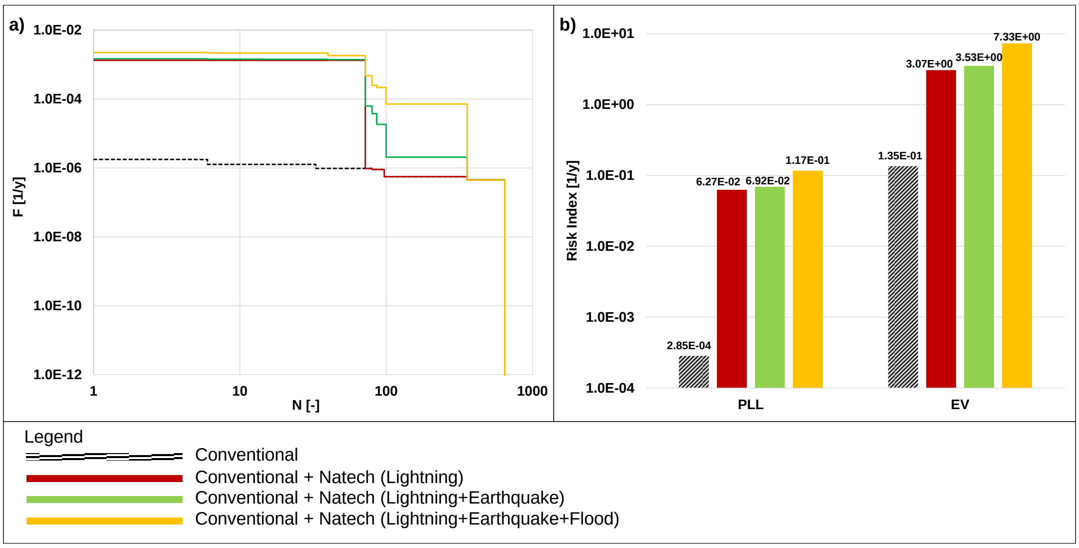

Figure 3: Societal risk figures calculated for the case study, expressed by: a) F/N curves; and b) Potential Life Loss (PLL) and expectation value (EV) risk indices.

For the sake of clarity, EV and PLL indices were also calculated, as reported in Figure 3b. Considering lightning-induced scenarios, the PLL and EV respectively increase of about 220 and 23 times compared to conventional

scenarios only. If also earthquake-induced scenarios are added, the relative increase of PLL and EV compared to conventional scenarios reach respectively a factor of 242 and 26. Finally, considering also flood-induced scenarios a severe increase in the PLL compared to conventional scenarios (of about 410 times) and a substantial increase in the EV (of about 54 times) due to the higher severity scenarios involved are spotted.
The last step of the new methodology allows to give a risk-based natural hazard ranking (Step 9). This can be easily done in light of the results obtained so far, in particular analysing the societal risk and PLL and EV indexes obtained. Therefore, the relative contribution of each natural hazard to the overall increase in risk indexes (i.e., the difference between the overall risk, in yellow in Figure 3b, and the conventional risk, in black in Figure 3b) was evaluated. Considering the PLL, the relative contributions of lightning, earthquake and flood-induced scenarios are respectively 53.7%, 5.6% and 40.7% while if the EV is considered the relative contributions are 40.8%, 6.4% and 52.8% respectively. This is in line with the indications given by LSIR curves of Figure 2, and lightning and flood-induced scenarios should be prioritized over earthquake-induced scenarios (that contribute only to about 6% of overall risk increase). It is possible also to compare lightning and flood-induced scenarios: in particular, if the PLL is considered, lighting scenarios contribution to overall risk increase (53.7%) is slightly higher with respect to the one associated to Natech scenarios triggered by flood (40.7%), while if a more severe social perception is associated to higher magnitude scenarios, the EV can be considered, clearly indicating that the flood-induced scenarios should be prioritized instead.

5. Conclusions

In this study, a methodology for Natech multi-risk assessment is presented. The methodology is based on a multi-hazard approach and enables the evaluation of Natech risk due to different reference natural events, enabling their ranking from a technological risk standpoint. The methodology is applied to a case study considering earthquake, lightning strikes, and flood-induced scenarios. The evaluation of the relative contribution of each natural hazard to the overall risk successfully produced useful indications on which natural hazards should be prioritized in Natech risk mitigation strategies.

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