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An Innovative Framework for Chemical and Process Facilities to Support a Comprehensive Natech Risk Assessment

Alessio Misuri, Valerio Cozzani*

Laboratory of Industrial Safety and Environmental Sustainability – DICAM, University of Bologna, Bologna, Italy
valerio.cozzani@unibo.it

The interaction between natural hazards and technological installations handling hazardous materials can produce complex cascading accidents termed as Natech events. Climate change and increasing vulnerability of industrial facilities caused a growing concern towards Natech hazards in recent years. Current methodologies addressing the identification and quantification of Natech scenarios mostly consider only the possibility of direct damage of process and storage equipment caused by natural hazards as earthquakes and floods. Nevertheless, recent severe Natech events as the Arkema accident (2017) demonstrated that the direct failure of equipment is not the sole possible accident trigger. Indeed, in these events the accident sequence was initiated by the impairment of auxiliary systems and utilities induced by the natural event. The present contribution proposes an innovative comprehensive framework to the identification of Natech scenarios and to the quantitative assessment of Natech risk. The new framework presented addresses the identification of both direct and indirect Natech scenarios and considers the possible failure of utilities in the evolution of the accident chain and in the escalation of accident consequences. Specific strategies for the identification of alternative routes leading to Natech events are suggested, considering loss of containment events caused either by the direct damage of equipment or by the failure of utilities or safety barriers. A test-case was defined to show the application of the framework. The results demonstrated the importance of the indirect route in determining the overall hazard due to Natech events when specific categories of hazardous substances are present on the site.

1. Introduction

When natural disasters impact industrial installations where hazardous materials are stored and processed, severe cascading scenarios can be triggered. Indeed, natural events can cause technological scenarios as fires, explosions or toxic releases. This typology of accidents falls under the definition of Natech events in the technical literature (Krausmann et al., 2017). The incidence of Natech events in industrial accident databases is significant, as highlighted by a recent study of Ricci et al. (2021), and is particularly critical from a societal risk standpoint. Moreover, climate change is expected to enhance the severity of climate and weather-related catastrophes (IPCC, 2018), which might in turn enhance the occurrence of Natech events (Mahan and Liserio, 2018).

These compound events are complex, and in the last decades several dedicated methodologies were developed to perform their assessment (Suarez-Paba et al., 2019). For instance, the European Commission developed the RAPID-N online tool to support authorities in assessing the risk posed by Natech events (Girgin and Krausmann, 2013). Several other authors proposed structured methodologies based on the chemical and process Quantitative Risk Assessment (QRA) rationale, as discussed in Mesa-Gómez et al. (2020). In some studies, more refined graphical statistical tools were also proposed (Khakzad and Van Gelder, 2018).

Most of the methodologies available for Natech risk assessment and management to date are focused on the severe scenarios following substance releases caused by the structural damage of process equipment or storage tanks during intense natural events. These methodologies are thus based on the paradigm shown in Figure 1a, accounting only for technological scenarios in "direct" accident paths (blue arrows in Figure 1), and including the possibility of accident escalation through domino effect (yellow arrows in Figure 1). The latter step in the Natech accident chain has been recently recognized by some authors (e.g., see (Naderpour and Khakzad, 2018)). Nonetheless, there is a clear evidence in past accidents that also utilities as power connection can be

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concurrently impacted during severe natural disasters as earthquakes (Girgin, 2011) and floods (BARPI, 2018). In addition, past accident analysis evidenced that also safety systems in place to prevent or mitigate accidents can be impacted, possibly losing their functionality (Misuri et al., 2019). However, neither the role of the impairment of utilities in generating technological scenarios nor the lowered level of protection provided by depleted safety barriers are considered in Figure 1a. To overcome this limitation, the new Natech accident paradigm shown in Figure 1b has been recently proposed by Misuri and Cozzani (2021).

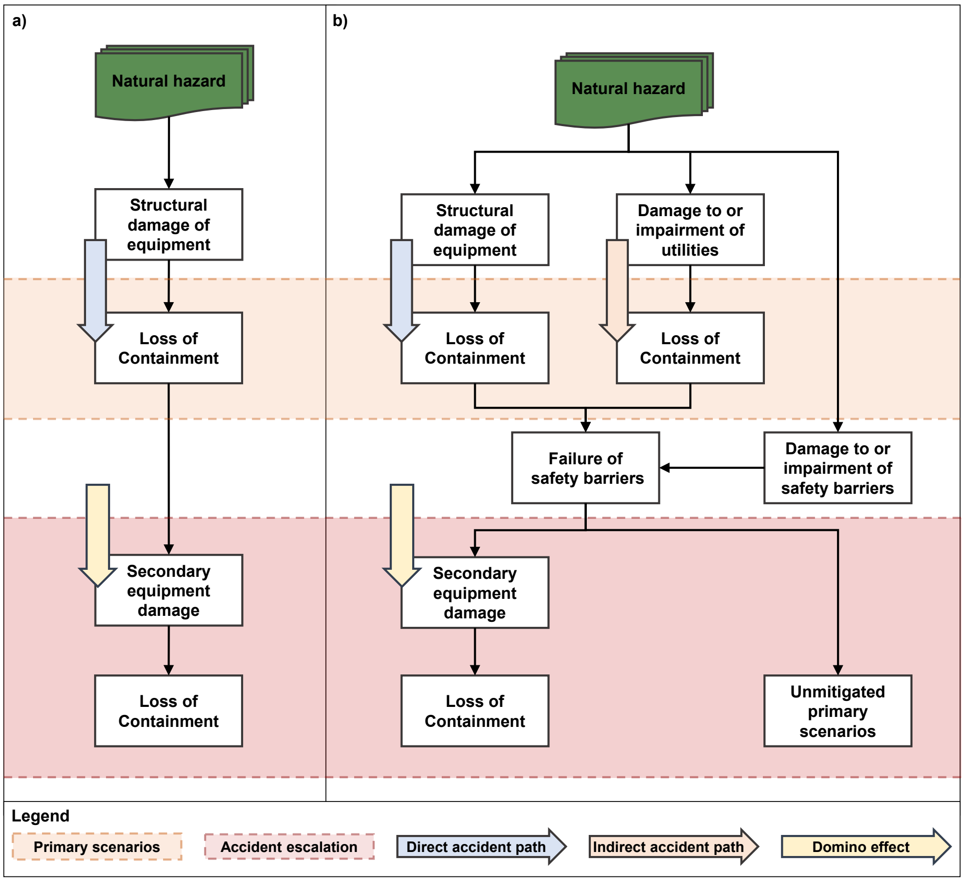

Figure 1: Comparison between the current Natech accident paradigm on which previous QRA methodologies are based (panel a), and the updated paradigm (panel b). Adapted from (Misuri and Cozzani, 2021).

As can be noticed comparing Figure 1b to Figure 1a, an additional accidental path has been considered, to address the possibility that technological scenarios generated by the impairment or by the damage of site utilities as power connections, instrument air, cooling systems (red arrow in the Figure 1b). This accident path becomes important when substances with specific features are handled in the site and require the correct operation of utilities to guarantee safe conditions. A reference list of substances which might lead to Natech scenarios via the indirect accident path is reported in Misuri and Cozzani (2021). In addition, the new paradigm recognizes the central role of safety barriers in determining the possibility of accident escalation both in unmitigated primary scenarios and in the propagation of the event through domino effect, features that fall outside the scope of the previous approaches to Natech QRA.

The new paradigm allows a better hazard identification, enabling the analysis of complex Natech accidents that could not be fully described through the previous methodologies. An example of severe Natech event whose evolution can be represented only through the new paradigm is the accident that involved an Arkema plant in Crosby, TX, during Hurricane Harvey in 2017 (CSB, 2018). The description of this accident through the rationale of Figure 1b will be presented in the next section. Then, a roadmap for the implementation of the updated paradigm in a comprehensive approach to the Natech QRA will be described (see Section 3). In Section 4, the application of the methodology will be exemplified through the definition of a notional case study. Lastly, some conclusions will be drawn in Section 5.

2. The Arkema accident (2017)

The Natech event involved an Arkema organic peroxide production site in Crosby, TX, during Hurricane Harvey, a severe tropical storm that made landfall in Texas and Louisiana in late August 2017 (CSB, 2018). The timeline of the main events that led to the Natech event are summarized in Table 1.

Table 1: Timeline of the main events during the Arkema accident (2017) (CSB, 2018).

Day	Description
August 25th	The tropical storm Harvey intensifies in a Category 4 Hurricane and makes landfall in Corpus Christi, TX. Arkema site is shut down in preparation of the hurricane.
August 26th	Plant shutdown is completed and a ride-out crew is on site. The rain intensifies and the water level flooding the plant starts to rise.
August 27th	Water level keeps rising and approaches electrical equipment. A subset of the low-temperature warehouses are turned off, and organic peroxides are moved into refrigerated trailers and to other low-temperature warehouses.
August 28th	Electrical transformers are reached by floodwaters and backup generators are started. Floodwater level rises forcing the shutdown of backup generators. The N_2 back cooling system cannot be operated due to flange submersion. Forklifts are inoperable and workers move all the peroxides into nine refrigerated trailers, three of which cannot be moved to higher ground location.
August 29th	The situation is out of control, all the workers at the facility are evacuated and an exclusion zone of 2.4 km radius around the site is issued by authorities.
August 31st	Organic peroxides into one trailer start to decompose due to temperature rise and caught fire generating a toxic black plume.
September 1st	Two more trailers caught fire.
September 3rd	The peroxide conditions inside the remaining trailers cannot be monitored. The six trailers are intentionally ignited by authorities.

As can be noticed by looking at Table 1, in the case of the Arkema accident, there was no release of hazardous substances due to the direct damage of the containment caused by the flood. Differently, the concurrent unavailability of cooling systems and the depletion of the safety barriers in place (i.e., the N_2 backup cooling system, and the refrigerated trailers) led to the impossibility to keep the heat-sensitive substance under safe storage conditions, and eventually to the severe fires. Hence, the Arkema accident evolution followed the indirect path of Figure 1b, as shown in the simplified event tree depicted in Figure 2.

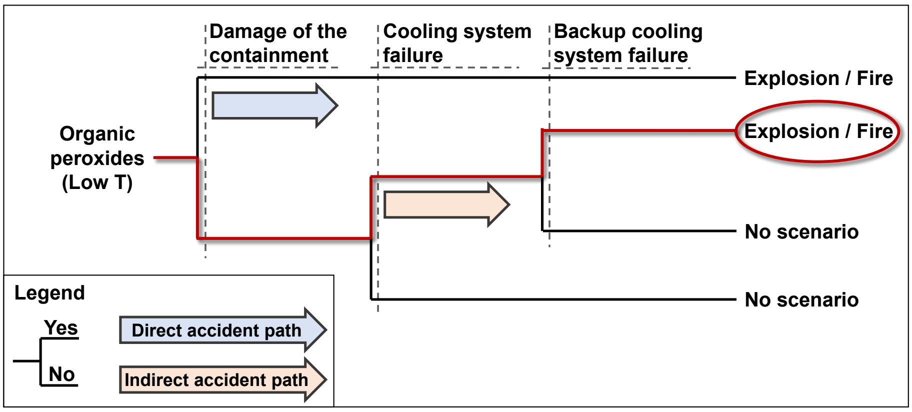

Figure 2: Simplified event tree highlighting that the Arkema accident followed the indirect accident path (red bold line). The accident paths are defined consistently with Figure 1b.

Therefore, the Arkema accident is a clear example of a severe Natech event that falls out of the capabilities of previous Natech QRA approaches, which assume that a structural failure of containment exerted by reference natural events is necessary to produce primary technological scenarios. In this case, instead, the warehouses where the peroxide was stored did not undergo significant structural damages during the flooding, although the unavailability of utilities still caused an accident.

3. Updated framework for the quantitative risk assessment of Natech accidents

The Arkema accident is not the only past event that cannot be assessed by the previous Natech QRA methodologies, and other examples have been identified in (Misuri and Cozzani, 2021). A comprehensive Natech risk assessment requires the implementation of the paradigm of Figure 1b in a holistic approach, accounting for the two accident evolution paths. The roadmap presented in Figure 3 has been thus conceived specifically to drive the analysis including also scenarios related with the systemic failure of the site.

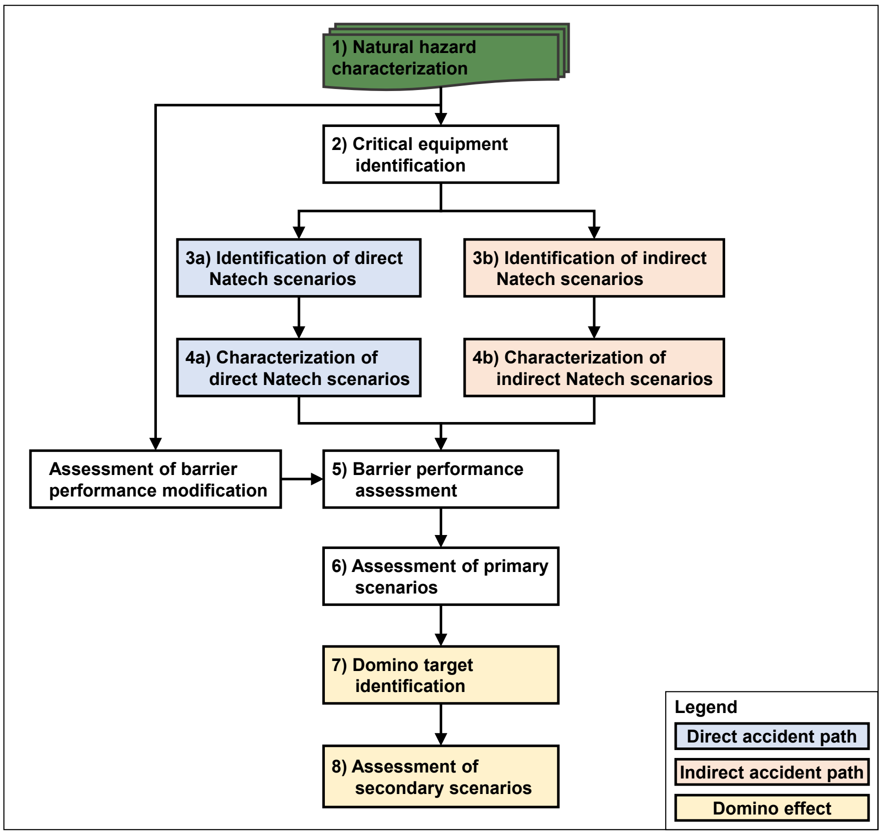

Figure 3: Roadmap to perform a comprehensive Natech QRA based on the updated accident paradigm shown in Figure 1b. Steps in blue are related to the direct accident path, steps in red are related to the indirect accident path, and steps in yellow to the domino effect. Adapted from (Misuri and Cozzani, 2021).

In analogy with previous Natech QRA approaches, after the initial characterization of the natural hazards by sufficiently simple methods, the critical equipment in the layout are identified (Krausmann et al., 2017). Then, the two separate accident paths shown in the paradigm of Figure 1b are assessed separately in the QRA methodology of Figure 3. On the left-hand side, the two steps in blue are aimed at identifying and characterizing the releases according to the direct accident path by means of vulnerability models (e.g., see (Landucci et al., 2014)) or fragility models (e.g., see (Salzano et al., 2003)). On the right-hand side, the two steps in red are instead conceived to assess the possibility of scenarios following the indirect accident path. In general, indirect Natech scenarios might happen when i) there is a failure of a utility system (e.g., electricity, cooling or heating fluids, N_2 inert gas, instrument air), and ii) substances not stable in the conditions occurring after process shutdown are handled/stored in the site. A reference list of substance categories that might lead to indirect Natech scenarios, organized by the hazard statements reported in GHS classification (United Nations, 2019) and CLP regulation (European Commission, 2008), is reported in Misuri and Cozzani (2021) and can be used to support the Step 3b of Figure 3. Unfortunately, specific approaches to perform the characterization and quantitative assessment of indirect scenarios (Step 4b in Figure 3) are lacking, thus only conservative estimates can be made to date. Then, a dedicated step to the assessment of safety barriers is included. This step is intended to evaluate the modification of safety barrier performance during the reference natural event and to consider their depletion in the assessment of primary scenarios (Step 6 in Figure 3) and in the evaluation of the possibility of domino effects (Steps 7 and 8 in yellow in Figure 3). Specific methodologies have been recently proposed in the literature to accomplish this task (Misuri et al., 2021).

4. Case study

A notional case study is defined to show the application of the methodology of Figure 3. A horizontal tank storing 40 ton of $SiCl_4$ at 3.5bar has been considered. The substance is classified as 'EUH014: Reacts violently with water', since it releases toxic HCl reacting violently with water or atmospheric moisture (European Commission, 2008). Inert gas (typically N_2) is used for blanketing ensuring safe storage conditions (GSC, 2017). The blanketing system is supposed to feature a baseline Probability of Failure on Demand (PFD) equal to 10^{-3}. A flood with f_{nat} = 2.0×10^{-3} y^{-1}, 2m water height and 1m/s velocity is assumed. Three Loss of Containment (LOC) events (i.e., instantaneous release, 10-min release and 10-mm release) were assumed as benchmark conventional scenarios with reference frequencies (Uijt de Haag & Ale, 2005). The direct damage probability is assessed at P_d = 4.7×10^{-1} by means of the model of (Landucci et al., 2014). The frequency of the indirect path is assessed tailoring the PFD to the case of flood by the modification factor of 0.5 (Misuri et al., 2020), obtaining PFD = 5.01×10^{-1}. The quantified event tree considering both direct and indirect accident paths is shown in Figure 4. Conservatively, a 10-min release has been assumed for consequence simulation of both direct and indirect Natech scenarios.

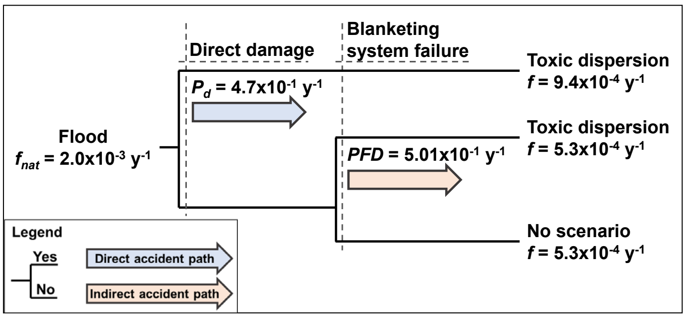

Figure 4: Quantified event tree for the case study, including both the direct and indirect accident paths.

The results obtained for the case study are shown in Figure 5. Risk figures obtained considering Natech scenarios both from the direct and indirect accident paths (continuous lines in Figure 5) are compared against the results obtained considering only direct scenarios as in previous Natech QRA approaches (dashed lines in Figure 5), and against the conventional scenarios selected as benchmarks (dotted lines in Figure 5). As can be seen from Figure 5a, including indirect scenarios leads to a significant increase of the local specific individual risk (LSIR) level the area is exposed to. The same effect is reflected on the increase of societal risk figures, as shown in Figure 5b.

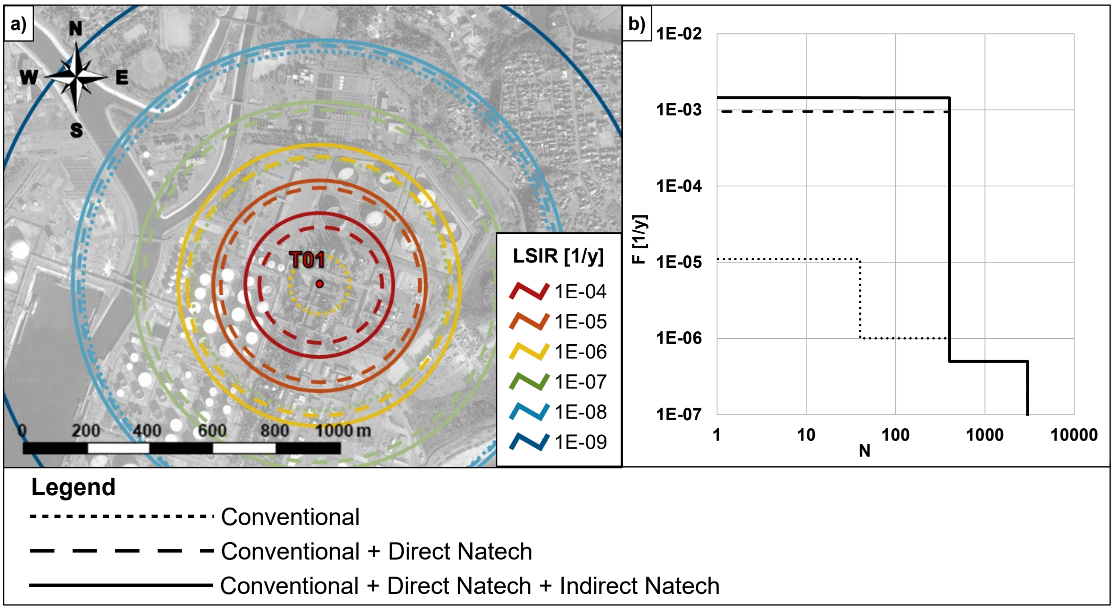

Figure 5: Results obtained for the case study in terms of LSIR contours (panel a) and F/N curves (panel b).

5. Conclusions

An innovative framework to support Natech risk assessment in chemical and process industries was presented. The framework is based on an updated accident paradigm that considers both direct scenarios following the damage of main equipment and indirect scenarios caused by the failure of critical utilities implemented to guarantee the safe storage of particular classes of substances. The framework also highlights the central role of barrier depletion during natural hazards in determining accident dynamics. The framework was applied to a case study, evidencing its value in supporting an improved identification of the scenarios and in producing more realistic risk figures. Overall, the approach paves the way to a more effective risk management of Natech events.

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