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The Role of Emergency Response in Risk Management of Cascading Events Caused by Natech Accidents

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Accidents triggered by natural events are becoming an increasing issue for policy-makers and industrial practitioners in the last decades. These events are called Natech (natural hazards triggering technological disasters), and their study is critical due to an increase in both the frequency and the magnitude of the consequences. Considering the possible failure of safety systems and the several equipment items potentially involved in the accidents due to the occurrence of multiple simultaneous failures and cascading events, the emergency response results to be a crucial aspect in the risk assessment and management of Natech events. Despite this, the emergency response can also be affected by the occurrence of natural events. The purpose of the present work is to understand the effects of natural events on emergency response. To reach this goal, some relevant past accidents are studied. The result of the analysis allows highlighting the effects of the natural events on the emergency response. Moreover, lessons learned on the critical elements of the emergency response are derived when considering Natech accidents and related cascading events.

1. Introduction

Causal analysis of technological accidents is essential to prevent similar future accidents or mitigate their consequences. Natural events may cause unique types of technological scenarios involving the release of hazardous substances, the so-called Natech accident (i.e., natural hazards triggering technological disasters) (Showalter and Myers, 1994). Typically, Natech accidents are erroneously associated with the occurrence of catastrophic natural disasters (e.g., earthquake, flood, tsunami), exclusively. However, in principle, they can be triggered by any kind of natural event (Casson Moreno et al., 2019), including low magnitude ones such as lightning and extreme temperatures (Ricci et al., 2020). Natech accidents have attracted the attention of academic researchers, industrial practitioners, and policy-makers (Nascimento and Alencar, 2016) due to their uncertain and complex nature, increasing occurrence, and severe consequences of major accidents scenarios if they happen (Krausmann et al., 2017). The increase in the number of natural events in the last decades has led to a growing number of Natech accidents (Ricci et al., 2021a). Moreover, the magnitude of the accident can escalate when it is triggered by a natural event. In fact, Natech accidents can be characterized by the possibility of multiple simultaneous failures (such as explosion, loss of containment, and fire) (Krausmann and Cruz, 2013), the occurrence of cascading events (domino effect) (Misuri et al., 2020a), and the disruption of utilities, safety systems, and lifelines (Misuri et al., 2021a). All these factors have promoted the study of Natech accidents over the last years. Particular attention has been devoted to the development of methodologies to calculate the failure probability of industrial items in the case of different natural events, such as earthquakes (Salzano et al., 2009), floods (Landucci et al., 2014), or lightning (Necci et al., 2013). Other works focused on the definition of safety distances, such as in the case of wildfire (Ricci et al., 2021c). Another important aspect is the possible disruption of safety systems due to natural events (Misuri et al., 2020b). In this context, the evaluation of the probability of failure and the effectiveness of safety barriers (mainly active and passive barriers) has been addressed (Misuri

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et al., 2021b). Other than active and passive barriers, human intervention during accidents plays a vital role in mitigating the effects of technological scenarios and avoiding cascading events (Landucci et al., 2015). The emergency response aims to safeguard human life, the environment, or other surrounding facilities and infrastructures possibly involved in the primary and secondary scenarios (Flynn, 2009). The effectiveness and efficiency of emergency response actions determine the propagation of an accident and potential cascading events. Hence, it represents a key aspect in determining the overall consequences deriving from the accident (Landucci et al., 2015). The recent modernization of the chemical and process industries driven by Industry 4.0 leads to continuous improvements of monitoring systems thanks to the automation of processes. Despite this, human intervention during accidents is still a crucial element for plant safety.
Upon a comprehensive literature study, scarce attention has been devoted to the study of emergency response in the case of natural events despite the criticality of the issue. Considering the complexity of the phenomena involved, past accidents represent the only source of detailed and complete information. The analysis of such events highlights vital elements to be considered to realize adequate guidelines and improve existing procedures. In fact, some actions can be delayed or unsuccessfully completed because of specific contingencies. Moreover, technical elements required to correctly implement the designed procedures can be damaged or unavailable due to the natural event. Neglecting these factors would turn into inappropriate actuation of the emergency response plans, thus reducing the effectiveness of the intervention. Additionally, it would lead to an underestimation of the overall risk in the framework of the quantitative risk assessment of Natech accidents and related domino effects. To fill this gap, the present work aims to address the issue of emergency response in the case of natural events. Thus, an analysis of relevant past accidents has been carried out. Results of the analysis allow identifying the effects of natural events on the emergency response in the case of Natech accidents. Moreover, the actions of emergency response teams that can be hindered by natural events are highlighted. Eventually, the framework of emergency management in Natech events will be addressed, focusing on the key issues relevant for the escalation of Natech scenarios.

2. Emergency response

This section introduces the concept of emergency response, providing a specific perspective for the cascading events and the Natech case.
The emergency response is widely considered a procedural safety barrier (Yuan et al., 2022). Its role in risk assessment and management is paramount, as derived from the Layer of Protection Analysis (CCPS, 2001). Despite the relevance of the issue, limited attention has been paid to the study of the emergency response due to complexity and the variety of actions and technical requirements needed to complete the procedures. In fact, the emergency response requires both human actions and technical needs to be effectively performed. Moreover, requirements change as a function of the aim of the intervention and the type of target considered. Human health, environment, and assets are the three main targets of emergency response (Flynn, 2009). A schematic representation of the targets and examples of the related actions is provided in Figure 1.

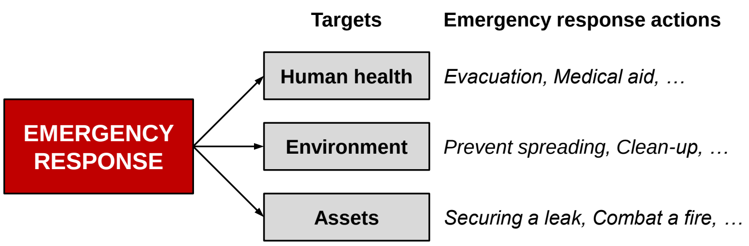

Figure 1: Representation of emergency response targets and examples of related actions.

As for human health, the emergency response can be addressed, for example, to the evacuation of an industrial site and/or the surrounding area. Again, it can be used to provide medical aid to the victims of the accidents. When considering the environment, the emergency response can be aimed at preventing the spreading of hazardous substances using containment means. Clean-up operations are another example of emergency response used to protect the environment. Eventually, emergency response can be focused on assets. Securing a leak or combating a fire are typical examples. These operations can reduce both the economic loss associated with the accident and its consequences, also limiting the probability of cascading events. As a result, the protection of the assets can decrease the overall magnitude of the consequences related to the accident, thus having a beneficial effect on the protection of human health and the environment.

The emergency response results to be paramount in avoiding the occurrence of cascading events when considering fire-driven domino effects (Landucci et al., 2015). Accidents in which the outcome is a fire are characterized by a time-lapse between the start of the primary fire and its spreading to neighbouring tanks due to the damage mechanism that is the so-called time to failure (Ricci et al., 2021b). Therefore, the time to failure of tanks represents the time available to perform an effective emergency response to avoid cascading events.
When considering a Natech accident, the possible failure of safety systems, as well as the large number of equipment items potentially involved, should be considered (Misuri et al., 2021a). These factors make the emergency response a crucial aspect in the risk assessment and management of Natech events. Despite this, the natural event itself can significantly affect the emergency response, limiting the availability of teams and technical supporting means. Furthermore, natural events typically do not impact only the industrial site but also the entire surrounding area, causing a greater demand for resources on the overall impacted area (Krausmann et al., 2017). In addition, the specific characteristics of Natech accidents can also affect the emergency response. In these cases, the emergency response should consider the possibility of occurrence of multiple simultaneous failures on the site. Eventually, the possible failure of safety systems, as well as utility systems, compromises the emergency response in the case of Natech events, thus reducing the likelihood and effectiveness of a first response provided by technical systems (Misuri et al., 2021b).
For a proper risk assessment and management, it is therefore paramount to consider all these factors when evaluating the emergency response. To do this, it is necessary to understand which aspects of the emergency response can be compromised by the Natech accident and by the natural event itself.

3. Past accidents analysis

Natural events analyzed in the present work are the Kocaeli earthquake and the Great East Japan earthquake and tsunami. For the sake of brevity, only elements relevant from the point of view of the emergency response are reported. More information can be found in the reference literature and the literature cited therein.

3.1 Kocaeli earthquake, Turkey, 1999

On August 17th, 1999, at 3 a.m., an earthquake of magnitude Mw=7.4 (Richter scale) struck an area of about 41,500 km^2 in Turkey, from Istanbul to the City of Bolu (Cruz and Steinberg, 2005). The area affected was densely populated and highly industrialized, and hundreds of industrial fields were hit by the earthquake (Krausmann et al., 2017). The described earthquake triggered several accidents in the fields. A multitude of fires, toxic releases, and spills to sea and soil have been reported, demonstrating that earthquakes can trigger multiple and simultaneous hazardous material releases (Steinberg and Cruz, 2004). Among the others, the accidents that occurred at an acrylic fibre plant and a refinery in Izmit Bay can be identified as the most relevant accidents based on caused damages. The former resulted in a toxic gas dispersion of acrylonitrile (i.e., a highly toxic, flammable, and volatile liquid), whereas the latter ended up in multiple fires. Considering the aim of this work, the second accident was selected for further analyses since the occurrence of the domino effect. In the following, an overview of the accidental dynamics, together with information on the emergency response, is reported based on the detailed description provided by Girgin (Girgin, 2011).
Immediately after the earthquake, three fires were reported in different locations inside the plant. The first one has been generated by the release of flammable chemicals due to the failure of the glass containment. The fire was extinguished in less than half an hour. The second one involved crude oil released by heater and pipelines struck by the collapse of a tower. After four hours, firefighters put out the fire, which reignited twice until the flow from the pipelines was stopped in the late evening. Eventually, the third fire occurred in the naphtha storage area, involving four floating roof tanks that ignited simultaneously. At the same time, a flange connection was damaged by the earthquake, causing a leak of naphtha into the open-ditch drainage system, and the fire was spread among two more tanks situated 200 m away from the primary fire.
Several teams have provided support at the refinery, such as the military, the municipalities, and neighbouring facilities fire-fighting teams. Additional support has been provided using airplanes. The failure of the national grid left the industrial site without electrical supply, and the failure of the pumping system together with water supply pipelines turned into the unavailability of fire-fighting water at the site. Besides, the occurrence of unexpected multiple simultaneous fires caused a shortage in the fire-fighting foam, thus hampering the response activities. Eventually, alternative sources of water, such as seawater, were used with scarce effectiveness because of the inadequate design of the diesel pump.

3.2 Great East Japan earthquake and tsunami, Japan, 2011

On March 11th, 2011, an undersea earthquake of magnitude Mw=9.0 (Richter scale) occurred off the Pacific coast of Tohoku (Krausmann et al., 2017). The earthquake affected a large part of Japan and caused the release of hazardous materials from many industrial installations. Besides, it also triggered a tsunami of great

magnitude, which worsened the situation, further damaging industrial sites and spreading released materials over vast areas with the floodwaters (Krausmann and Cruz, 2013). Thousands of industrial fields were damaged by the earthquake (Zama et al., 2012) and tsunami, and hundreds of hazardous material releases were reported (Wada and Wakakura, 2011). Among the reported releases of toxic and flammable substances, the most relevant are the fire and explosion that occurred in the LPG storage tank farm in Tokyo Bay and the fires at a refinery in the Sendai port area. In the former, 17 tanks were destroyed by the accident. It was triggered by the failure of an LPG tank filled with water due to maintenance procedures during the earthquake. The higher density of water with respect to LPG compromised the structural integrity of the tank, which was designed to withstand the stress caused by the earthquake when filled with LPG. The impact with the nearby tanks caused a leak of LPG from the connection pipes that subsequently ignited, heating the content of the adjacent tanks that turned out in boiling liquid expanding vapour explosion (BLEVE) and fireball. The whole LPG tank farm was rapidly involved in the accident. Furthermore, missiles from the explosion damaged other tanks located in the proximity causing the spill onto the ground and the sea of asphalt and eventually generating other fires in two adjacent companies. Because of the magnitude of the accident, fire-fighting teams decided to let the fire burn until the fuel was exhausted despite the involvement of local, regional, and national supporting teams.
The second accident considered related to the Great East Japan earthquake and tsunami is the one that occurred in the Sendai port, where multiple fires were reported. Major leakages of heavy oil have been experienced caused by the failure of pipelines and tanks. A multitude of minor spills of hazardous materials has been occurred throughout the entire industrial site because of the damages caused by both the tsunami and the earthquake. One of the fires occurred in the loading area due to the rupture of a pipeline used for the unloading process. In the same area, multiple other pipeline breaks have been caused by the tsunami leading to releases and fires, which eventually consumed a significant section of the plant.
Emergency teams were aware of fires due to smoke coming from the facility. Nevertheless, the debris created and transported by the tsunami had made roads impassable, leading to the inaccessibility of the site. Moreover, communications during the crisis were inadequate to provide a fast and effective response to the accident. Indeed, only four days later, the emergency response actions could start, as soon as the accessibility to the site had been restored. However, the fire-fighting equipment had to be carried by hand due to impediments still present inside the plant. On-site fire-fighting equipment was inoperable due to the damages caused by the tsunami.

4. Discussion

As revealed by the events described in the previous section, safety barriers alone cannot be enough the prevent the accident or reduce the consequences. This can be due to the failure of safety systems or their inadequacy in case of events of such high magnitude. For this reason, the role of emergency response in risk management in the case of Natech accidents become crucial to effectively mitigate the consequences. Nevertheless, the emergency response can also be affected by natural events. Thus, understanding the possible effects of natural events on the emergency response is paramount to performing it efficiently.
The information available for accidents that occurred after the Kocaeli earthquake revealed several shortcomings related to the emergency response in the case of an earthquake. Based on the described accidents, lesson learned can be grouped as follow:

- Inadequate design of mitigation safety systems. Namely, fire-fighting equipment, water-based and foam-based mitigation systems. As an example, hoses were not long enough to reach industrial items located in a distant part of the site. Moreover, sprinkler systems were implemented in a limited number of tanks, not considering the possible occurrence of multiple simultaneous fires.
- Inadequate capacity of fire-fighting materials to tackle multiple and simultaneous fires. The shortage of fire-fighting materials represented one of the main issues for the emergency response. The capacity of the fire-fighting materials on site is a paramount factor that should be considered in the case of Natech accidents, especially due to the high probability of multiple simultaneous failures that can occur. Moreover, the material shortage became even more critical when considering the occurrence of cascading events. The shortage of fire-fighting material affects the effectiveness of both the emergency response and safety systems such as sprinkler systems and water deluge.
- Damage or failure of utility systems. Lack of the main power supply, as well as the unavailability of the fire-fighting system (e.g., water tank pumps and pipelines), are typical examples of this category. The design of utility systems should be done considering the possible failure of primary systems, thus implementing adequate backup systems for critical elements. As a result of the accident, diesel pumps present on site were not suitable to effectively counteract the fires.
- Inadequate size of the internal fire-fighting team. This is demonstrated by the request for a multitude of external supporting teams. This assumes an additional relevance considering that emergency teams have

to face simultaneously the accidents and the consequences of the natural event itself. Hence, the possible unavailability of supporting teams should be considered and properly evaluated.

Some of the characteristics described were found to be common to the accidents that occurred following the Great East Japan earthquake and tsunami. The latter accidents, moreover, highlight some other criticalities in emergency response, as listed below:

- Inadequate training for any emergency teams specific for the case of Natech accidents and related cascading events. As mainly revealed by the accidents in the LPG storage tank farm in Tokyo Bay, the emergency teams were not adequately trained to counteract the multiple fires, despite the huge number of support teams available.
- Inappropriate emergency response plans for Natech accidents and related cascading events. Besides the inadequate training of emergency teams, the accident that occurred in the LPG storage tank farm also revealed that the emergency response plan was not suitable for the several cascading events triggered by Natech accidents.
- Possible disruption of external infrastructure leading to inaccessibility of the site. For example, roads and bridges can be critically damaged, hampering the arrival of emergency teams and equipment on the scene, as shown in the accident that occurred in the Sendai port. This shows that the response to the emergency is not only hindered by internal factors but also that the external infrastructures should also be considered. This means, for example, that the emergency response plans should consider the possible inaccessibility of the primary route, directing new routes to reach the site when this happens.
- Inadequate communication to effectively face the natural event emergency and related accidents. This can result from both the possible disruption of standard communication means and an incomplete set of information shared within the teams.

Even if both the accidents considered relate to earthquakes, the lesson learned from their analysis is valuable to address the issue of the emergency response in Natech accidents. Earthquakes are one of the more catastrophic natural events, and, for this reason, they are more prone to cause Natech accidents. In addition, due to their characteristics, earthquakes quickly impact the surrounding areas and safety systems, making it one of the most complex natural events also from the point of view of emergency response management.

Lessons learned provide the starting point for the evaluation of the effects of natural events on emergency response. Thus, a summary of the emergency response elements identified as affected by natural events is reported in Table 1. Considering these aspects in the risk assessment and management allows not to underestimate the risk associated with Natech events and improve the emergency response plans of industrial sites. Knowing in advance what can go wrong allows one to plan the emergency response correctly.

Table 1: Synoptic table on emergency response elements identified according to accidents considered

Emergency response elements	Kocaeli earthquake Turkey, 1999	Great East Japan earthquake and tsunami, Japan, 2011
Inadequate design of mitigation safety systems	X	
Inadequate capacity of fire-fighting materials	X	
Damage or failure of utility systems	X	X
Inadequate size of the internal fire-fighting team	X	X
Inadequate training for any emergency teams		X
Inappropriate emergency response plans	X	X
Disruption of external infrastructure		X
Inadequate communication		X

5. Conclusions

Natech accidents (natural hazards triggering technological disasters) have attracted attention in the last decades due to their uncertain and complex nature, increasing occurrence, and severe consequences. The magnitude of the accident can escalate when it is triggered by a natural event due to the possibility of multiple simultaneous failures, the occurrence of cascading events, and the disruption of utilities, safety systems, and lifelines. All these features reveal that emergency response is crucial in the risk assessment and management of Natech events. Nevertheless, the study of past accidents demonstrates that natural events can also affect emergency response. Lessons learnt pointed out some main criticalities of the emergency response in the case of Natech accidents. These aspects revealed a lack in the emergency response plans when considering natural events. The results of the present work can be used as a starting point for a correct evaluation of the emergency response in the framework of Natech risk assessment. Eventually, lessons learned can guide an improvement of existing emergency response plans specifically for natural events and Natech accidents.

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