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ANALYSIS OF TECHNOLOGICAL ACCIDENTS TRIGGERED BY NATURAL EVENTS (NATECH) IN THE PERSPECTIVE OF CLIMATE CHANGE

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ABSTRACT

The severe accidents deriving from the impact of natural events on industrial installations have become a matter of growing concern in the last decades. Actually, high impact cascading events may arise when natural hazards hit installations where large amounts of hazardous substances are stored, as in the case of the chemical and energy industry. In the literature, technological accidents caused by the impact of natural events on industrial installations are typically referred to as Natech accidents. These events have several peculiarities which distinguish them from conventional industrial accidents caused by internal factors. Indeed, Natech accidents are characterized by the possible occurrence of multiple simultaneous failures of equipment items, and natural events enhance the probability of cascading events. Moreover, utility and safety systems may also be affected by natural events worsening the consequences related to Natech accidents.

From this perspective, the research project provides a comprehensive overview of Natech accidents that occurred in the Chemical and Process Industry. The analysis allows for the identification of relevant aspects of Natech events, such as the natural events more likely to trigger Natech scenarios, and the technological scenarios that arise. Moreover, quantified event trees and probability of ignition are derived from the collected dataset, providing a step forward in the quantitative risk assessment of Natech accidents.

The investigation of past Natech accidents also demonstrated that wildfires may cause technological accidents. In addition, climate change and global warming are promoting the conditions for wildfire development and rapid spread, dramatically reducing the time of return of such events. For this reason, ensuring the safety of industrial facilities exposed to wildfires is paramount. This was achieved defining safety distances between wildland vegetation and industrial equipment items which avoid the spread of wildfires inside the plant. Nevertheless, safety distances cannot always be guaranteed. In this perspective, the assessment of vulnerability of the plant to wildfire events is very important. To this aim, an innovative methodology for the vulnerability assessment of Natech and Domino scenarios triggered by wildfires was developed. The approach accounted for the dynamic behaviour of wildfire events and related technological scenarios. The results of a case study suggests that the emergency response plays an important role in the vulnerability of the plant. Besides, emergency response may be hampered by the occurrence of natural events. For these reasons, a methodology for the evaluation of the emergency response was developed. As a result, the performance of the emergency response and the related intervention time in the case of cascading events caused by natural events were evaluated.

Overall, the tools presented in this thesis represent a step forward in the Quantitative Risk Assessment of Natech accidents. The methodologies developed also provide a solid basis for the definition of effective strategies for risk mitigation and reduction. These aspects are crucial to improve the resilience of industrial plants to natural hazards, especially considering the effects that climate change may have on the severity of such events.

Chapter 1:
INTRODUCTION

1.1 Overview of Natech events

Natural disasters are a worldwide concern, potentially affecting any area of the world causing severe consequences for the population [1]. In the last decades, severe natural disasters such as earthquakes, floods, and hurricanes have dramatically hit several countries causing, among other consequences, relevant economic losses affecting the production processes [1]. Besides short-term effects, natural events have also affected production processes with long-term consequences due to the post-event plant shutdown, business interruption, and the loss of critical supply infrastructures [2].

Interactions between natural disasters and industries may result in technological scenarios, which worsen the consequences of the natural disasters themselves. These types of accidents are referred to as "*Natech*" and they were first introduced by Showalter and Meyers in 1994 [3], that defined them as:

"Natural disasters that create technological emergencies"

Since the specific features of this category of accidents were first recognized, the concern related to technological accidents triggered by natural disasters has grown within academia, industry, international organizations, emergency management agencies, and regulatory bodies [4–8]. This has promoted the study of Natech accidents, and several other definitions were proposed. A list of definitions available in the literature is reported in Table 1.1, adapted from the study of Nascimento and Alencar [5].

Table 1.1. List of definitions for the Natech accidents available in the literature. Adapted from Nascimento and Alencar [5].

Natech definition	References
Technological events caused by the impact of a natural event/natural disaster in an industrial plant.	[4,9–25]
Events impacting industrial plants, which cause damage to equipment and lead to the leakage of hazardous substances that can cause severe technological accidents.	[26–29]
Technological accidents involving the release of, or the potential release of, hazardous materials, triggered by a natural event.	[30]
Natural disasters that can cause major accidents in chemical and process facilities, which may result in the leakage of hazardous materials with damage to the processes, pipelines and storage units.	[31]
Natural disasters that can have serious consequences for critical infrastructures which on failing or being destroyed can impact plants, people, the environment and the economy.	[31–34]

In addition, the occurrence of severe Natech accidents, such as those caused by the Kocaeli earthquake in 1999 [25,35,36], hurricanes Rita and Katrina in 2005 [37–39], and the Great East Japan earthquake and tsunami in 2011 [20,40], demonstrated that not only natural events can trigger technological accidents, but also that the consequences can be serious. Indeed, Natech accidents may feature characteristics different from conventional accidents. The study of past events demonstrated that the occurrence of multiple simultaneous failures is possible during natural events and that the probability of domino effects leading to escalation is enhanced in Natech accidents [41]. Moreover, natural disasters may affect the utility systems, safety systems and lifelines. The natural events may also overload the emergency system, having to face both natural and technological disasters simultaneously, thus hindering and delaying rescue and recovery operations [2,42]. Eventually, several studies on Natech accidents showed that there seems to be a growing trend in terms of their frequency and severity [42–44].

1.2 Natural disasters and the role of climate change

Climate changes can cause modifications of extreme weather and climate events in terms of frequency, intensity, spatial extent, duration, and timing. These can lead to unprecedented extreme natural events [1]. As a result, the number of natural disasters is increasing worldwide since the beginning of the twentieth century as reported by the International Disaster Database EM-DAT developed by the Centre for Research on the Epidemiology of Disasters (CRED) [45]. Figure 1.1 reports the number of natural disasters over time as a function of the type (geophysical, hydrological, meteorological, and climatological events). Looking at the figure, geophysical phenomena seem to have a limited increase compared to other types of natural events. Indeed, these phenomena are typically less influenced by climate change, and their trend is therefore not surprising. On the contrary, climate-related events such as meteorological, hydrological and climatological events are increasing in number, especially from 1970 onwards.

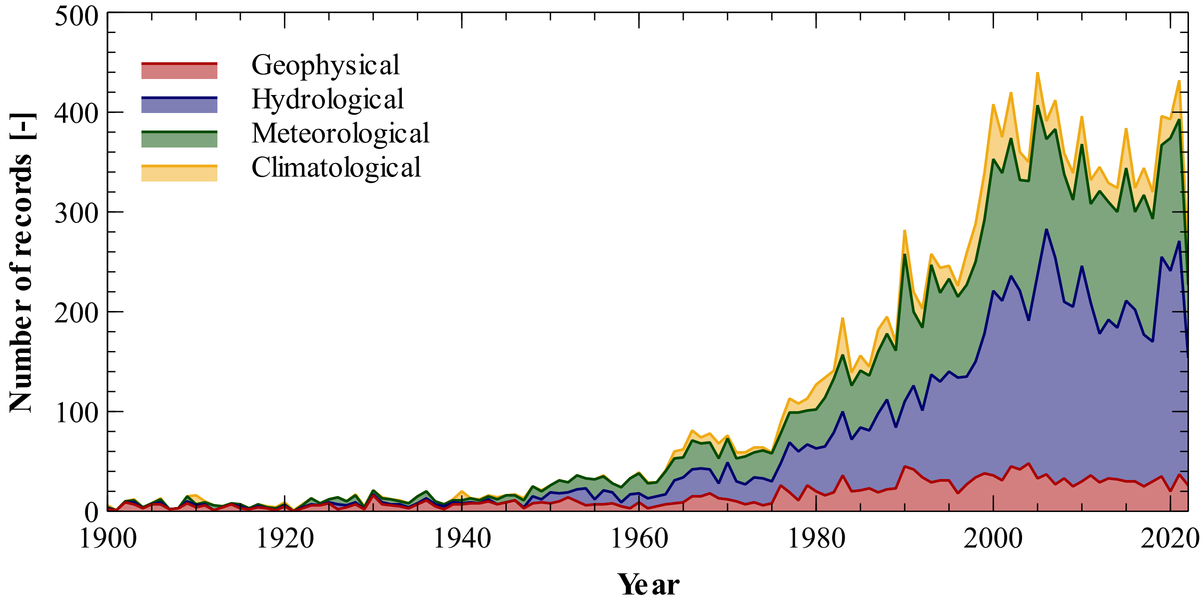

Figure 1.1. The number of natural disasters from 1900 according to the data provided by the International Disaster Database EM-DAT [45].

For weather and climate phenomena, statistics can be provided for temperatures, precipitations, winds, and other phenomena in terms of average, variability and extremes. Through the observation and analysis of past evidence, information on future trends can be derived [1,46]. From this perspective, the Intergovernmental Panel on Climate Change (IPCC) proposes in its special report "*managing the risks of extreme events and disasters to advance climate change adaptation*" an overview of the observed changes and a summary of projected changes at a global scale [1]. An excerpt of the results is reported in Table 1.2.

Table 1.2. Overview of the observed changes and a summary of projected changes at a global scale according to the Intergovernmental Panel on Climate Change [1].

Events		**Observed changes (since 1950)**	**Projected changes (up to 2100)**
Weather and climate variables	Temperature	*Very likely* decrease of cold days. *Very likely* increase of warm days. *Medium confidence* in the increase in length or number of heat waves.	*Virtually certain* decrease in frequency and magnitude of cold days. *Virtually certain* increase in frequency and magnitude of warm days. *Very likely* increase in length, frequency, and/or intensity of heat waves.
	Precipitation	*Likely* statistically significant increases in the number of heavy precipitation events.	*Likely* increase in the frequency of heavy precipitation events or increase in the proportion of total rainfall from heavy falls.
Phenomena related to weather and climate extremes	Tropical cyclones	*Low confidence* that any observed long-term increases in tropical cyclone activity are robust.	*Likely* decrease or no change in the frequency of tropical cyclones. *Likely* increase in mean maximum wind speed. *Likely* increase in heavy rainfall associated with tropical cyclones.
	Extratropical cyclones	*Likely* poleward shift in extratropical cyclones. *Low confidence* in regional changes in intensity.	*Likely* impacts on regional cyclone activity. *Low confidence* in detailed regional projections. *Medium confidence* in a reduction in the numbers of mid-latitude storms. *Medium confidence* in the projected poleward shift of mid-latitude storm tracks.
Impact on physical environment	Droughts	*Medium confidence* that some regions of the world have experienced more intense and longer droughts (but opposite trends also exist).	*Medium confidence* in the projected increase in duration and intensity of droughts in some regions.
	Floods	*Limited to medium evidence* is available to assess climate-driven observed changes in the magnitude and frequency of floods at a regional scale. *High confidence* in the trend toward the earlier occurrence of spring peak river flows in snowmelt- and glacier-fed rivers.	*Low confidence* in global projections of changes in flood magnitude and frequency. *Medium confidence* that projected increases in heavy precipitation would contribute to rain-generated local flooding. *Very likely* earlier spring peak flows in snowmelt- and glacier-fed rivers.

As highlighted also in Table 1.2, one of the most certain pieces of evidence of climate change is the increase in mean temperature and the related extremes. Indeed, according to the NASA Scientific Visualization Studio [47], the earth's surface temperature in 2021 was the sixth warmest in records. In addition, the same source reports also an increase of 0.85°C in the global temperatures in 2021, confirming the long-term warming trend. For the sake of completeness, colour maps that display a progression of changing global surface temperature anomalies are reported in Figure 1.2.

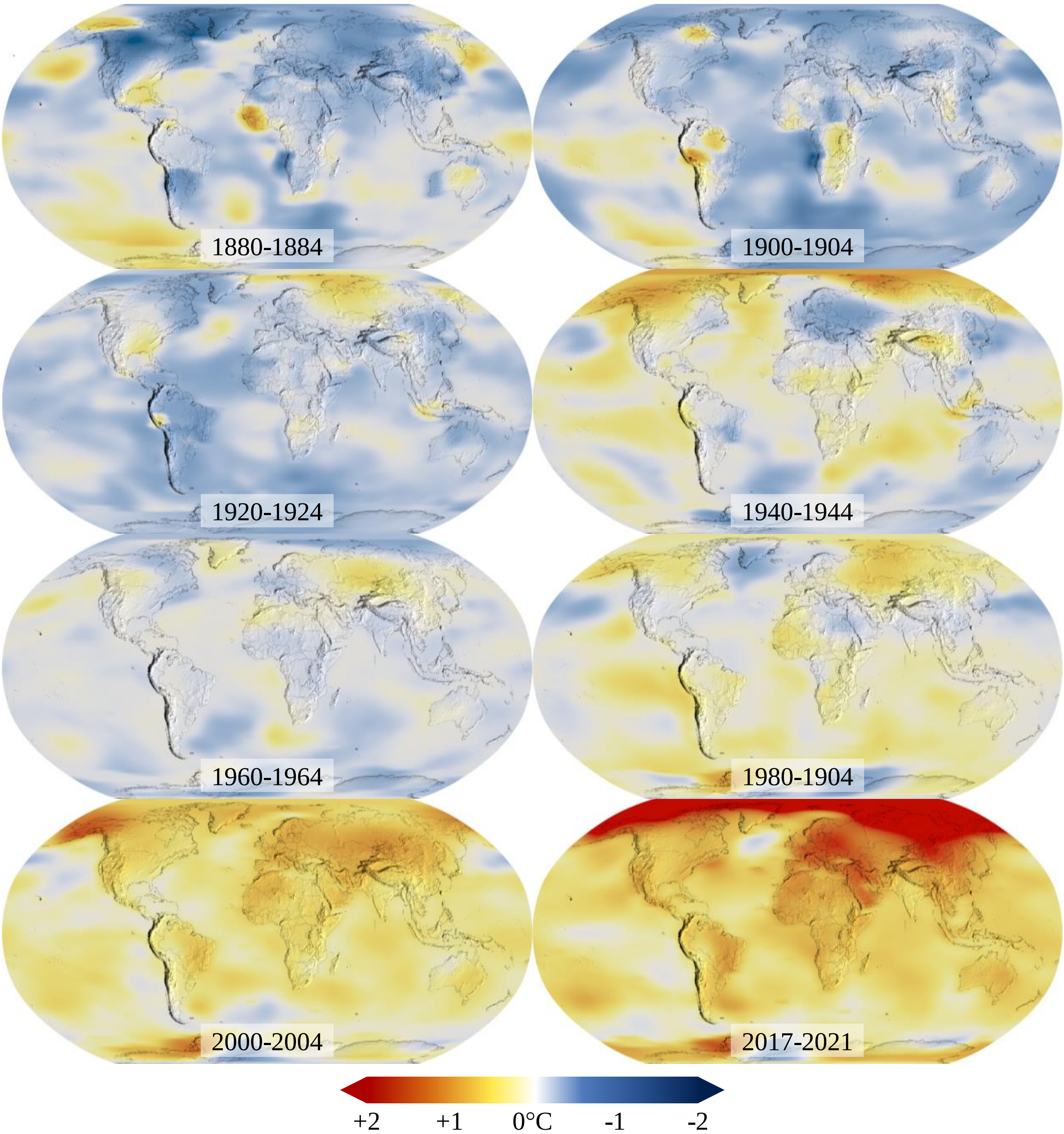

Figure 1.2. Colour maps that display a progression of changing global surface temperature anomalies. Adapted from the NASA Scientific Visualization Studio [47].

Together with the increase in the mean temperature, Table 1.2 also reports that some regions of the world have experienced and will probably experience in future years more intense and longer droughts.

Thus, global warming is lengthening hot and dry seasons, strongly influencing fire regimes and promoting the conditions for the ignition and the rapid spread of forest fires [48–53]. Indeed, increases in both the number of large fires [54] and the burned area [53,55] have been documented over the last decades across the western United States of America (USA) and in other fire-prone areas [56,57]. Extremely intense wildfires have occurred worldwide in recent years, such as those observed in Portugal in 2017 [58], Greece in 2018 [59], and California in 2020 [60,61]. Moreover, according to a study by Jolly and co-workers [62], fire weather seasons have lengthened by about 19 % between 1979 and 2013, further increasing wildfire risk and severity. As a way of example, Figure 1.3 shows the average burned area per fire in the United States of America over the last 39 years according to the data provided by the National Interagency Fire Center [63]. Looking at the figure, it is clear that the trend (red line) is on the whole growing, even if fluctuations occur from year to year (grey bars).

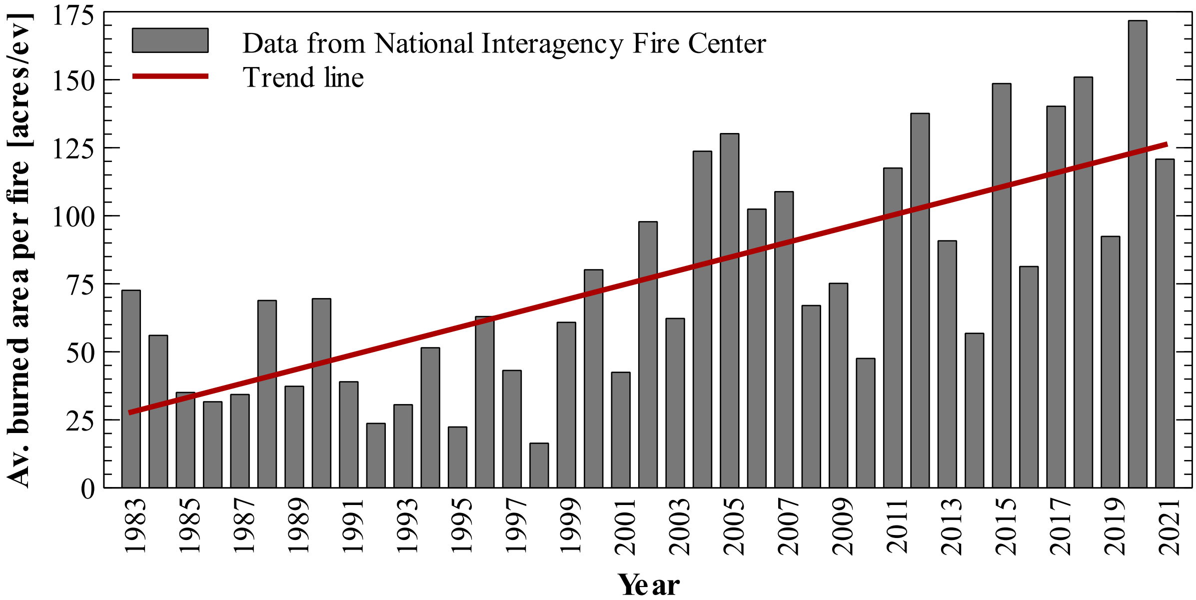

Figure 1.3. The average burned area from a wildfire event over the years for the United States of America. Data source: National Interagency Fire Center [63].

Other natural phenomena affected by climate changes are precipitations and related extremes. Precipitations are expected to increase globally, even if with significant differences at regional levels. Indeed, some tropical regions and high latitude areas will probably experience an increase in precipitations, while the opposite is expected in subtropical regions [46,64,65]. In addition, climate model projections suggest that extreme precipitations will probably increase and that changes in extreme precipitations are expected to be larger than those in mean precipitations [46,64–66]. Besides precipitations, global warming also contributes to the increase in the amount of water in the global atmosphere. Indeed, an increase of 7% is expected in the atmospheric moisture for each degree of temperature rise [46], albeit the change is not expected to be at a global scale [67,68]. Both these factors are leading to changes in the overall hydrological cycle [46,68] and they are enhancing the probability of flood occurrence [1]. In addition, according to Kundzewicz and co-workers, floods are already impacted by climate change [1,69]. This is somehow confirmed by the trend of hydrological events reported in Figure 1.1.

Eventually, the increase in the number of past natural disasters reported in Figure 1.1 and the projections of future changes in the climate reported in Table 1.2 raise concern about the future occurrence of Natech accidents, both in terms of frequency and magnitude. Indeed, natural disasters are the root cause of Natech events and each change in their behaviour may affect also the occurrence of related technological scenarios.

1.3 State of the art

The occurrence of severe Natech accidents, the increasing frequency of natural events, and the severe consequences associated with these accidents promoted their study in the last decades. The present section aims at providing the state-of-the-art on Natech accidents. Firstly, an overview of the literature available related to the qualitative and semi-quantitative analysis is presented in Section 1.3.1. Then, a focus on the studies related to the quantitative risk assessment of Natech events is reported in Section 1.3.2. Eventually, a final section is devoted to the inclusion of safety barriers in the Natech quantitative risk assessment (Section 1.3.3).

1.3.1 Qualitative and semi-quantitative studies

Krausmann and co-workers [32] focused their attention on the emerging issue of Natech accidents by trying to understand their underlying causes, outlining the ongoing efforts in the development of methodologies for Natech assessment, and introducing the topic of emergency response and early warning in such events. Similarly, Salzano and co-workers [2] provide information on available tools and knowledge gaps in the assessment of Natech events, focusing attention on the potential impact of lightning, earthquakes, and floods. Besides, the implementation of strategies for Natech risk management reduction became paramount, as introduced by Krausmann and co-workers in several studies [70,71]. In line with these works, Reniers and co-workers developed a conceptual framework that allows for making chemical clusters more resilient to natural disasters [72].

Being Natech accidents a relatively new topic, a large variety of information can be obtained by studying accidents that occurred in the past. Several works focused on the study of a single past event, such as the analysis of the impact of the Wenchuan earthquake on industrial facilities that occurred in 2008 [73], or the lesson learnt derived by Misuri and co-workers related to Hurricane Harvey that hit several industrial facilities in 2019 [74], in addition to the literature relating to the Kocaeli earthquake, hurricanes Rita and Katrina, and the Great East Japan earthquake and tsunami cited previously.

To provide a better understanding of the features of Natech accidents, historical analyses were carried out by several authors based on the retrieval of a wide dataset of Natech accidents. For example, Cozzani and co-workers analysed the industrial accidents triggered by flood events [21], while Renni and co-workers focused their attention on lightning events [75]. Both the studies present an overall analysis of the collected events, focusing their attention on the equipment items involved in the accidents and the development of qualitative post-release event trees for the specific natural events under analysis. Krausmann and co-workers developed a wider dataset but the natural events analyzed are still limited to earthquakes, floods, and lightning [31]. Other authors focused their attention on the study of Natech accidents that occurred in the United States of America regardless of the triggering natural events, such as the work proposed by Sengul and co-workers [26] and Luo and co-workers [76]. For the same geographic area, Girgin and Krausmann further narrowed the analysis to study accidents related to onshore hazardous liquid pipelines [77], while Santella and co-workers built a specific database to estimate empirical conditional probabilities of Natech events [27]. Eventually, Kumasaki and co-workers performed a classification of the physical effects of natural hazards on industrial installations based on a Japanese database [78]. Noteworthy, all the studies presented focused their attention on specific aspects of natural events or they are developed for specific geographical areas. Thus, despite the great effort in understanding Natech behaviour, a comprehensive analysis of the occurrence of Natech accidents in the chemical and process industry is still missing.

1.3.2 Studies on Natech quantitative risk assessment

Besides the qualitative and semi-quantitative analysis, an ongoing effort is devoted to the definition of quantitative methodology to perform the Natech quantitative risk assessment. In this perspective, Cozzani and co-workers proposed a general framework for the quantitative assessment of Natech scenarios in complex industrial areas, which summarizes the existing methodologies and provides a guideline for the development of subsequent approaches for specific events of concern [79]. The outline of the proposed methodology is reported in Figure 1.4. In the following sections, the state-of-the-art on quantitative assessment of Natech accidents is presented.

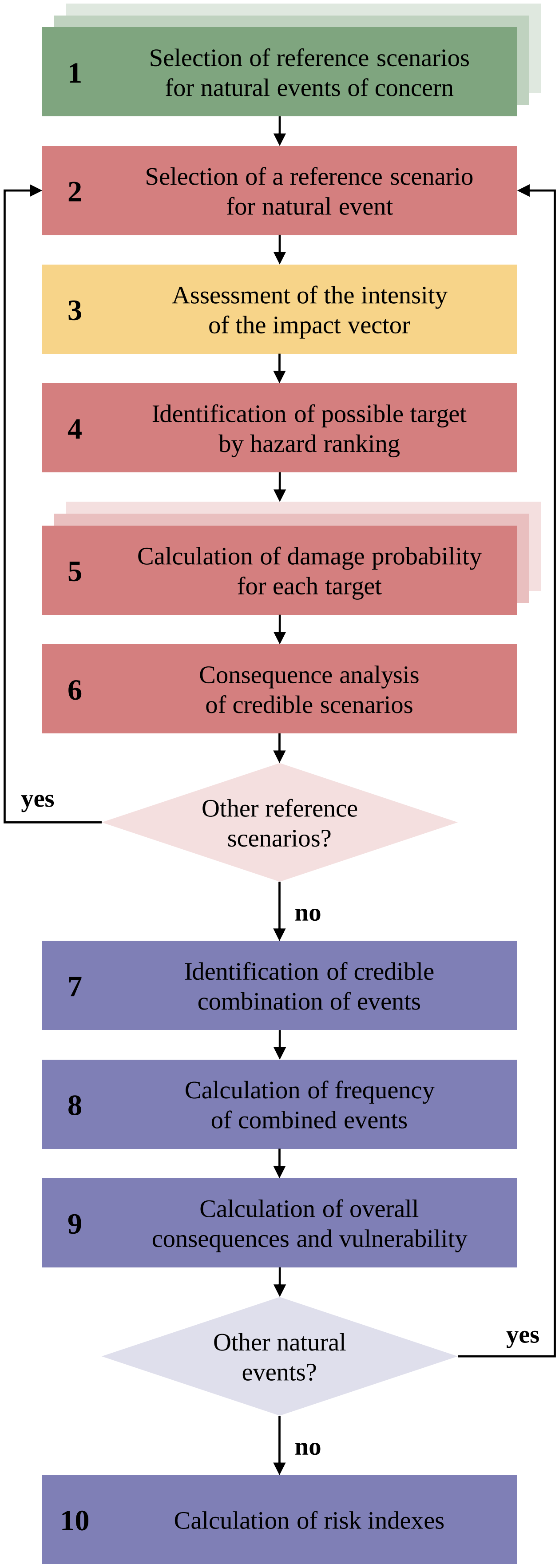

Figure 1.4. Flowchart of the procedures proposed for quantitative risk assessment of Natech scenarios by Cozzani and co-workers. Adapted from [79].

1.3.2.1 Earthquakes

Concerning earthquakes, specific methodologies were proposed by Antonioni and co-workers [80] and Campedel and co-workers [81], presenting flowcharts similar to the one proposed in Figure 1.4. Both methodologies are developed to perform the Natech QRA of industrial sites. A different target was instead considered by Zanini and co-workers, that focused their attention on the natural gas distribution networks [82]. Kabir and co-workers proposed a different methodological approach that makes use of a Bayesian belief network model to assess the seismic-related Natech risk [83]. In addition, Huang and co-workers an innovative quantitative methodology based on Monte Carlo simulation that accounts also for domino escalation scenarios [84]. All these methodologies make use of vulnerability models (mainly in the form of fragility curves) to calculate the damage probability of targets exposed to earthquakes, as required for example in Step 5 of the flowchart presented in Figure 1.4. Thus, efforts were dedicated also to quantifying the vulnerability of industrial targets to seismic events. For example, Lanzano and co-workers developed fragility curves for natural gas pipelines [14,85] while Salzano and co-workers focused on atmospheric storage tanks [86]. In addition, Salzano and co-workers subsequently expanded the types of equipment to horizontal pressurized storage tanks, pressurized reactors, and pumps [87]. Concerning pipelines and supporting structures, fragility curves were proposed also by Karagiannakis [88]. All the vulnerability models make use of the horizontal component of peak ground acceleration (*PGA*) to characterize the magnitude of earthquakes, and equations are typically given in the form of:

$$Y = k_1 + k_2 \cdot \ln\left(PGA\right) \qquad \text{Eq. 1.1}$$

Where Y is the probit variable, k_1 and k_2 are constants, and the *PGA* is given as a fraction of the gravitational acceleration g. The probit variable Y is then related to failure probability through an integration. Details of the procedure are reported elsewhere [86,87,89,90]. Coefficients k_1 and k_2 depend on the type of equipment considered, the filling level of the equipment (when meaningful), and the release state that accounts for the entity of the damage and the related loss of containment. Three release states are typically defined [86] which account for slightly affected items leading to a negligible loss of containment (*RS1*), structural damages to items giving rise to a slight loss of containment (*RS2*), and catastrophic failures of items resulting in a consistent and rapid total loss of containment (*RS3*). Eventually, Zuluaga Mayorga and co-workers developed parametric fragility curves for storage tanks considering both buckling and overturning as failure modes [91].

1.3.2.2 Floods

As for flood events, Antonioni and co-workers proposed a methodology for the quantitative risk assessment of primary scenarios with an approach similar to the one reported in Figure 1.4 [92]. Further developments were proposed by Zeng and co-workers which developed able to take into account domino effects triggered by floods [93]. Besides the definition of frameworks for the quantification of risk, the development of vulnerability models that account for the effects of floods on equipment items is paramount. In this perspective, pioneering works are those proposed by Landucci and co-workers, which developed simplified correlations to evaluate the failure probability of atmospheric storage tanks [94] and horizontal cylindrical vessels [95] based on the tank geometry and the magnitude of the flood events in terms of water height h_w and water velocity v_w. These correlations are derived by applying a structural detailed model to a wide set of tanks considering the buckling as a failure mode for atmospheric tanks [94] and the floatation in the case of horizontal cylindrical vessels [95]. Recently, further developments of the model are proposed by Caratozzolo and co-workers, which tailored the model to extend its application to horizontal vessels with internals [96]. In addition, Kameshwar and Padgett [97] proposed logit functions for the evaluation of fragility curves for anchored and unanchored aboveground storage tanks both considering buckling and floatation as failure modes. An approach based on logistic regression was instead proposed by Yang and co-workers to calculate fragility curves of atmospheric tanks considering failures due to displacement and buckling [98]. More comprehensive models are proposed by Khakzad and Van Gelder that account for the rigid sliding and the impact of debris as failure modes in addition to shell buckling and floatation [99,100]. These models are based on limit state equations and fragility functions are derived through logistic regression, Monte Carlo simulations and Bayesian network. In addition, in the same work proposed for earthquakes, Zuluaga Mayorga and co-workers developed also fragility curves in the case of flood events [91]. Eventually, Rossi and co-workers proposed a model for the vulnerability assessment of process pipelines [101]. Noteworthy, a general formulation of the vulnerability models as a function of the magnitude of the flood event (h_w and v_w) and the geometrical features of the targets is not available. For this reason, please refer to the specific literature of each model for details and applications.

1.3.2.3 Lightning

Besides earthquakes and floods, several efforts were dedicated also to the quantification of Natech accidents triggered by lightning. Necci and co-workers developed a methodology for the quantitative risk assessment of Natech accidents triggered by lightning [102]. The methodology proposed somehow reflects the general one proposed in Figure 1.4. Despite this, the methodology does not consider the possible failure of multiple items simultaneously. Thus, it is assumed that a single lightning strike can affect a single equipment item. Another methodology for the risk assessment of Natech accidents triggered by lightning is proposed by Cheng and Luo, which is based on a Bayesian network model [103]. Then, Misuri and co-workers tailored the methodology developed by Necci and co-workers extending its application to the assessment of the risk related to domino escalation scenarios[104]. In addition, Yang and co-workers also developed a method to predict the probability of domino effects triggered by lightning on chemical tank farms [105]. As for the previous cases, the vulnerability of equipment items should be evaluated. In the case of lightning, Necci and co-workers developed a damage model that considers the shell perforation and it provides as results the conditional probabilities of perforation following lightning impact and the related equivalent diameter of the hole [9]. In another study, the same authors also proposed a methodology to calculate the lightning impact frequency on process equipment [106]. Eventually, an event tree analysis was proposed by Necci and co-workers [28], which allows for identifying and quantifying the event sequences following lightning impact on atmospheric tanks also considering the presence of safety barriers.

1.3.2.4 Wildfires

The recent occurrence of extreme wildfire events, as reported in Section 1.2, promoted the investigation of safety aspects related to their interaction with human structures. Many researchers focused their attention on the Wildland-Urban Interface addressing the risks that may arise when an uncontrolled fire reaches urban areas in the last decades [107–109]. In addition, several studies were developed on the effects of wildfires on domestic LPG tanks [110–112], approaching the problem from an experimental and a numerical point of view. The Wildland-Industrial Interface, instead, started to attract attention only recently. Pioneering studies on wildfire front approaching industrial installations were carried out by Khakzad and co-workers [113,114]. These works are based on the use of the Dynamic Bayesian Network to evaluate the probability of the wildfire reaching industrial installations and the related spread inside the plant. Despite this, the authors focused their attention on the loss of revenue due to industrial operations shutdown rather than performing a complete quantitative risk assessment due to wildfire for industrial installations.

1.3.2.5 Miscellaneous

As can be observed by the results of literature reviews on Natech accidents [4–8], earthquakes, floods and lightning are the most studied natural events. For these natural events, methodologies for the quantitative risk assessment are quite complete and consolidated. Despite this, past accidents demonstrated that Natech events can be triggered by any kind of natural event, even those characterized by less severe magnitude [41,115]. Thus, the research also moved towards the study of the interactions between industrial sites and other natural events. For example, Olivar and co-workers developed a vulnerability model for atmospheric tanks exposed to extreme wind loads [116]. Similarly, Basco and Salzano focused their attention on tsunami events, proposing a fragility function to evaluate the vulnerability of equipment items both considering tsunami waves and debris [117]. Again about tsunami events, Cruz and co-workers analysed the impact of two tsunami scenarios at an oil refinery, drawing recommendations on safety measures to reduce the risk of an accident and mitigate the consequence [118]. Moreover, a model for the vulnerability assessment of atmospheric tanks exposed to hurricanes was developed by Qin and co-workers [119]. The model is based on a Bayesian network approach and it allows considering the filling of storage tanks with water before the advent of hurricanes as safety barriers.

1.3.3 Safety barriers assessment

The methodologies proposed in the previous sections for the quantitative risk assessment, and most of the methodologies available in the literature in general, are based on a common framework that is shown in Figure 1.5-a. The framework considers that accident scenarios arise from the failure of an equipment item directly affected by the natural event, which causes a loss of containment of hazardous substances ("*Direct path*" in Figure 1.5-a). Recently, some methodologies introduced the quantification of domino escalation scenarios ("*Domino*" in Figure 1.5-a) because of the structural damage of secondary equipment items due to the effect of the primary scenario [93,104,105].

Studies on past accident analysis showed that the direct path is the more recurrent event sequence in Natech events [21,31,41]. Despite this, recent events, such as the accident that occurred in the Arkema facility (Texas) following Hurricane Harvey [120] and the one in the Dai-ichi nuclear power station (Japan) during the Great East Japan earthquake and tsunami [121], suggested that other accidental pathways are possible. From this perspective, Misuri and Cozzani proposed a revision of the framework, which is reposted in Figure 1.5-b. The updated framework allows considering additional pathways ("*Indirect path*" in Figure 1.5-b) related to the failure of auxiliary systems, plant utilities, and safety barriers, which may play an important role in accident evolution that were not captured by the current approach for Natech risk assessment.

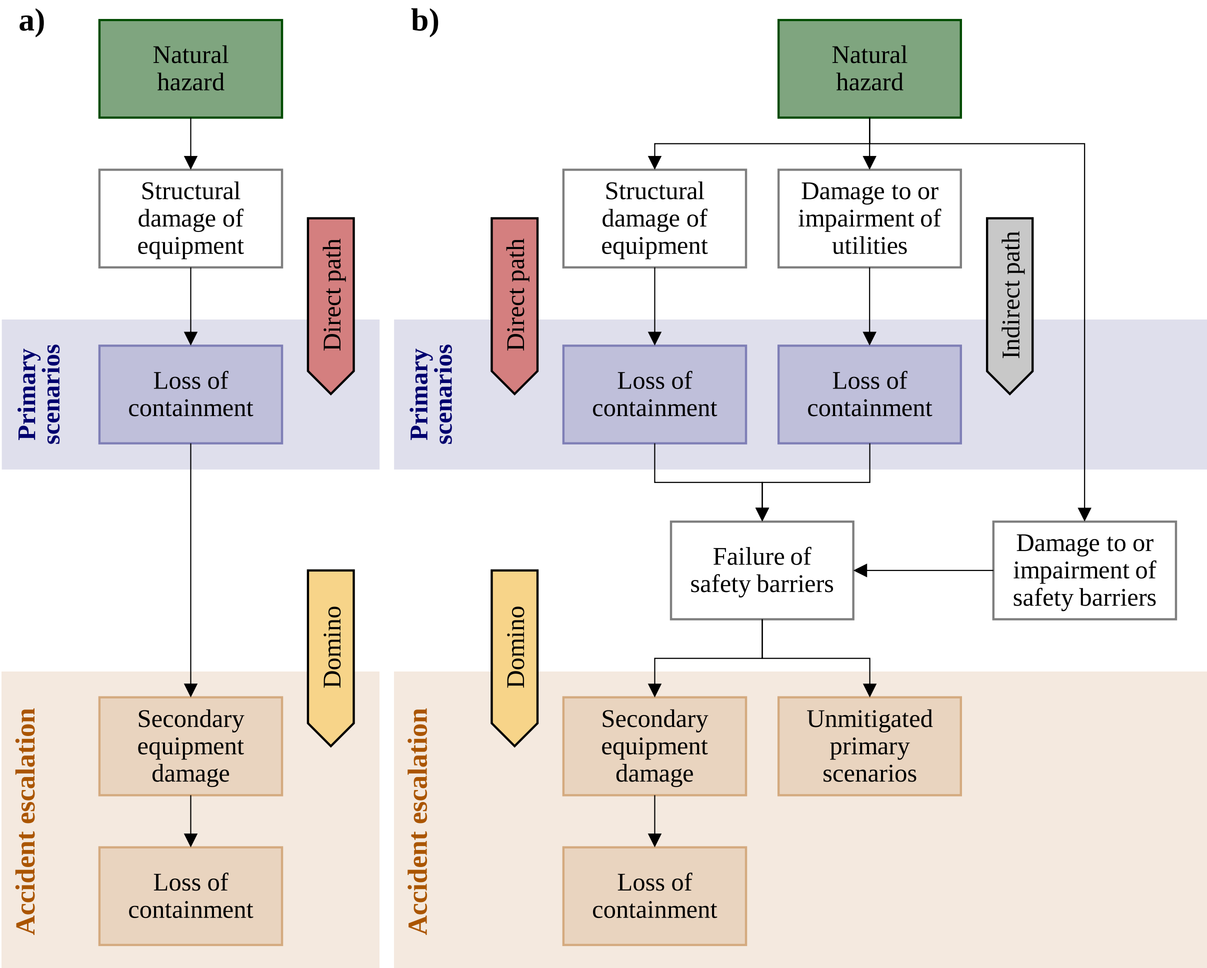

Figure 1.5. The framework adopted for the assessment of Natech events in the current literature (a) and the holistic framework proposed by Misuri and Cozzani [122] *for Natech risk assessment (b). Adapted from Misuri and Cozzani* [122,123].

Misuri and co-workers also dedicated several efforts to the study of safety barrier performance in the case of natural events. Indeed, they conducted an anonymous survey involving more than 40 experts which resulted in the performance quantification of a list of active and passive safety barriers in the case of earthquakes and floods [124]. Then, the results of the survey were used to quantify the frequency of mitigated and unmitigated scenarios in the case of domino scenarios [125]. Eventually, Misuri and co-workers tailored the methodology reported in Figure 1.4 to accommodate the possible degradation of safety barriers performance in the Natech quantitative risk assessment [126]. In the same work, a method to evaluate the barriers performance modification was also proposed, that is based on the fault tree analysis of the barrier under analysis.

Noteworthy, the methodology reported above considers only the effects of active and passive safety barriers. Nevertheless, procedural safety barriers play an important role in the case of major accidents and they can be affected by the natural events as well. Indeed, the emergency response operations may be hampered and delayed by the occurrence of the natural events, resulting less effective in relation with Natech accidents. Despite this, limited attention is devoted in the literature to the study of the emergency response in Natech accidents. A pioneering work is those carried out by Bernier and co-workers which addressed the issue of the site accessibility during storm surge events [127]. Another interesting work is those of Baser and Behnam that pointed out the need of a well developed emergency response plan for cascading post-earthquake fires that should take into account domino escalation scenarios and the inability to extinguish the possible multiple simultaneous fires [128].

1.4 Research questions

The concern related to Natech accidents increased in the last decades due to two main reasons. On the one hand, the number of natural events and disasters is increasing and projections suggest it will continue to grow in the future, as reported in Section 1.2. Being natural disasters the triggering factors of Natech accidents, this trend can be connected to the occurrence of such technological scenarios. Indeed, even if the vulnerability of industrial plants to natural phenomena can be much less than 1 (i.e., equipment items do not fail with certainty when hit by natural disasters), an increase in the number of Natech accidents in the next years is likely. On the other hand, the occurrence of Natech accidents caused by natural disasters of great magnitude (such as the Kocaeli earthquake in 1999, hurricanes Katrina and Rita in 2005, and the Great East Japan earthquake and tsunami in 2011) demonstrated that the consequences of such events can be more severe than those resulting from conventional accidents, possibly causing multiple simultaneous failures, cascading events, and the disruption of utility, safety systems and lifelines, as illustrated in Section 1.1. All these factors suggest that the consequences of Natech accidents are not negligible and that disregarding natural events as triggering factors of technological scenarios can lead to a significant underestimation of the risk.

An important source of information on Natech events is represented by accidents that occurred in the past. As reported in Section 1.3.1, several studies performed a historical analysis of Natech accidents. Despite this, the analyses performed were limited to specific natural events, technological scenarios or geographical areas of interest. Thus, a comprehensive analysis which allows characterizing the features of Natech events is still missing. In addition, some studies pointed out that the event trees in the case of Natech events may differ from those used in conventional accidents. Despite this, only qualitative analyses were carried out to date. Based on the above discussion, two research questions were formulated:

Which are the features of Natech events?
How to quantify event trees in the case of Natech accidents?

Besides the increasing number of natural events, climate change is promoting the conditions for the development of extreme natural events, both in terms of frequency and magnitude. Indeed, as reported in Section 1.2, one of the main effects of climate change is global warming, which leads to modification of mean temperature and related extremes. These changes are also modifying the hydrological cycle, thus influencing the frequency and the magnitude of flood events. In addition, global warming is lengthening hot and dry seasons promoting the condition for the ignition and the rapid spread of wildfires. Thus, particular attention should be devoted to the study of such events as they may become relevant in future years. Despite this, several studies were carried out concerning floods, and the methodologies for the quantitative risk assessment of flood-induced Natech accidents are quite robust, at least considering humans as the target. On the contrary, less attention was devoted to extreme temperatures and wildfires in the past, and the methodologies (when available) do not allow the development of a complete quantitative risk assessment. A step toward the characterization of such events can be obtained by answering the following question:

How extreme temperatures and wildfires can result in Natech accidents impacting industrial installations?

Although extreme temperatures can cause per-se technological scenarios, wildfires represent a significant hazard for industrial sites given also the severe consequences of the events themselves. In addition, wildfires can impact very wide areas, causing a risk for many industrial sites. Thus, priority should be given to the study of the interactions between wildfires and industrial plants. From a safety-related perspective, preventing the wildfire from spreading inside the plant and avoiding damage to equipment items is paramount. Hence, the following research question was formulated:

In the case of wildfires impacting industrial sites, how to ensure the safety of the plant?

Besides safety, it is also important to evaluate the vulnerability of industrial sites exposed to wildfire. Indeed, it is not always possible to guarantee the safety of the site (especially for existing industrial plants) and therefore it is paramount to evaluate the risk for the industrial site related to wildfire-induced accidents. Despite this, no methodology is available in the literature addressing the quantitative risk assessment of industrial accidents triggered by wildfire, as reported in Section 1.3.2.4. This lack paved the way for the following research question:

In the case of wildfires impacting industrial sites, how to assess the vulnerability of the plant?

Eventually, natural disasters may affect also safety barriers, utilities, lifelines, and emergency response, as demonstrated by several past events (see Section 1.1). From this perspective, an updated framework was proposed in the literature that allows considering additional pathways related to the failure of auxiliary systems, plant utilities, and safety barriers, as described in Section 1.3.3. In addition, some studies were carried out to evaluate the effects of natural events on safety barriers, and the risk modification in the case of their depletion. Despite this, only active and passive barriers were considered in such studies and procedural safety barriers, such as those concerning emergency response, were not accounted for. Nevertheless, emergency response may be hampered and delayed by natural events, such as earthquakes, floods, and wildfires, as it has to face both natural events and technological scenarios simultaneously. Thus, the inclusion of the effects of natural events on emergency response is paramount to not underestimate the risk. To this aim, the following research questions were formulated and answered:

Which are the effects of natural events on the emergency response?
How to measure them?

In this study, the above research questions were addressed also in the light of the current understanding and cutting-edge research available in the current literature. The gained information is paramount for the development of comprehensive knowledge on the subject.

1.5 Thesis outline

The present thesis consists in six chapters, including the present, following the outline of the research questions presented in Section 1.4. Thus, Chapter 2 reports a comprehensive overview of Natech accidents performed through the analysis of an extended database of technological scenarios triggered by natural events and disasters. In Chapter 3 a methodology for the definition of safety distances between wildfire and industrial installation is presented that allows for avoiding the spread of wildfire within the site. Then, Chapter 4 presents how to evaluate the vulnerability of industrial sites to wildfire proposing a tailored methodology for its assessment. In Chapter 5, the effects of natural events on the emergency response are investigated and evaluated. Eventually, conclusions from this research are drawn in Chapter 6 together with an outlook for future developments.

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Chapter 2:
A COMPREHENSIVE ANALYSIS OF NATECH ACCIDENTS IN THE CHEMICAL AND PROCESS INDUSTRY

Natech accidents that occurred in the past have demonstrated that interactions between natural events and industrial installations may cause severe consequences. A concrete understanding of the specific features of Natech accidents is becoming paramount. The present chapter aims at providing an overview of the features of Natech accidents that occurred in the chemical and process industry. This is done through the collection and analysis of an extended dataset of accidents. Information on the temporal and geographical distribution of the events is provided, together with the share among the natural events triggering the technological scenarios. A detailed analysis of the technological scenarios and of the substances involved in the accidents is presented. The severity of the Natech accidents is also evaluated in terms of damages to humans and assets. Eventually, a specific investigation addressing Natech events caused by extreme temperatures and wildfires is provided.

2.1 Introduction

In recent years, the number of meteorological events caused by short-term, medium-scale extreme weather conditions (lasting from minutes to days [1]) and climatological events caused by long-term, macro-scale atmospheric processes (ranging from intra-seasonal to multi-decadal climate variability [1]) is growing due to climate change, as widely explained in Section 1.2. These events become of concern for industrial activities when their interactions with the industrial installation may lead to adverse consequences, resulting in major accidents referred to as Natech accidents [2,3]. Furthermore, some particularly vulnerable areas of the world may experience intense natural hazards which have expected return times higher than those of conventional accidents for a single facility. For example, the frequency of a category 5 hurricane on the South Coast of the United States can be estimated at around $2 \cdot 10^{-2}$ events/year [4], while reference values for the tolerable frequencies of severe technological accidents are usually lower than $1 \cdot 10^{-5}$ events/year [5]. Thus, the frequency of severe Natech scenarios may result in higher values than that of conventional scenarios when a single production site is considered, even considering that the vulnerability of the site can be much lower than one. In addition, Section 1.1 pointed out that consequences that arise from Natech accidents may be more severe than those experienced in conventional accidents. Despite the increasing attention devoted to the topic (see Section 1.3), there still is no systematic tracking of industrial sites in natural-hazardous zones, and a systematic monitoring of Natech accidents is still missing [6]. In addition, Section 1.3 also highlighted the lack of a harmonized data collection system devoted to Natech, that could be used to point out relevant features of Natech accidents. From this perspective, the present chapter aims at answering the following question:

Which are the features of Natech events?

The question is answered by building an original dataset dedicated to Natech events, whose analysis allows a comprehensive understanding of Natech scenarios. A wide set of events were collected, related to the last 70 years. For these events, the time trend, the geographical distribution, the triggering natural events, the technological scenarios, and the hazardous substances involved in the accidents were analysed. In addition, the severity of the collected Natech events was evaluated both in terms of damages to humans and economic losses. An in-depth analysis of the technological scenarios as a function of the involved substances was then carried out, based on the wide dataset of records collected. This assessment resulted in the quantification of the probabilities of occurrence of each scenario, allowing the development of quantified even trees for some categories of hazardous substances and related probability of ignition. Thus, the results of the analysis answered the second research question:

How to quantify event trees in the case of Natech accidents?

Eventually, the database provides also useful information to characterize Natech accidents triggered by extreme temperature and wildfire, thus answering also the following research question:

How extreme temperatures and wildfires can result in Natech accidents impacting industrial installations?

This is achieved by performing a detailed analysis of the available records concerning extreme temperatures and wildfires. For these natural events, the possible routes through which they interact with industrial installation are recognized, paving the way to the further development of methodologies specifically addressing Natech events caused by extreme temperatures and wildfires.

The present chapter is organized as follows: Section 2.2 reports the methodology used to build the database, Section 2.3 shows the main features of Natech accidents, Section 2.4 is devoted to the development of quantified event trees, Sections 2.5 and 2.6 provide a focus on extreme temperature and wildfires respectively, and Section 2.7 presents some conclusions.

2.2 Building the database

The present section aims at providing information on the development of the database containing Natech accidents. First, the source consulted, and the keywords used for the search are presented (Section 2.2.1). Then, the inclusion criteria used to derive whether to consider or not a record in the database are defined (Section 2.2.2). Eventually, key information on the database structure is given (Section 2.2.3). A roadmap related to the development of the database is presented in Figure 2.1.

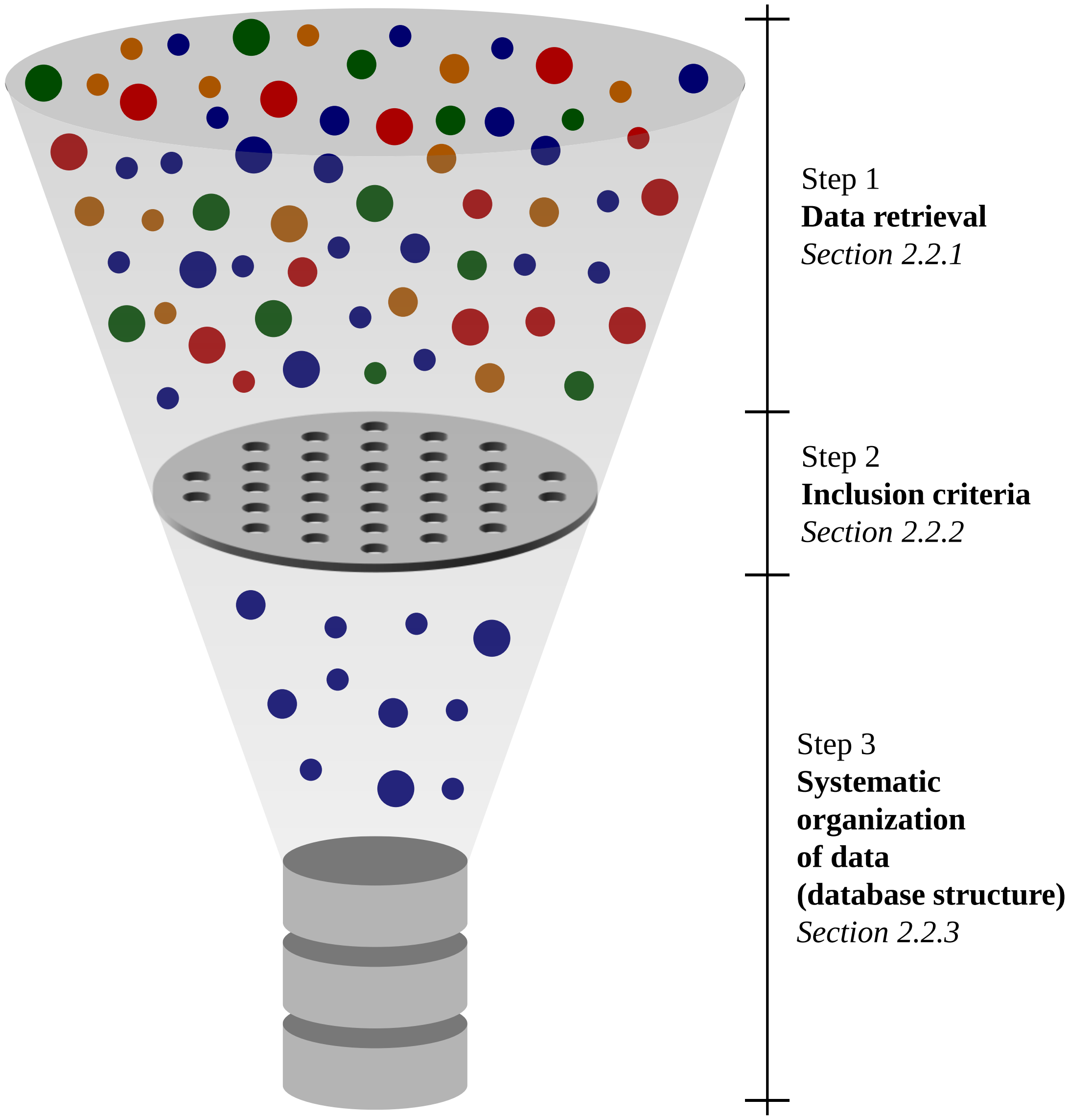


Figure 2.1. Roadmap for Natech past accident data collection and database development.

2.2.1 Data retrieval

As a first step, a set of sources was identified for the collection of accidental records triggered by natural events. All the sources consulted provide records on industrial accidents, even if not specifically on Natech events. Being the sources different and variegated in terms of datasets, of the period covered, and of the level of detail of the entries, a brief description of them is reported in the following:

- The eMARS database (Major Accident Reporting System) [7]. It is managed by European Commission's Joint Research Centre (JRC), and specifically by the European Major Accident Hazards Bureau (MAHB). It was established after the implementation of the first "Seveso" Directive (82/501/EEC) in 1982, and it is still active. The eMARS database contains information on accidents and near misses that occurred in the European Union, and the entries are obtained from the mandatory reporting system issues under the Seveso Directives. In addition, it collects event reports of other countries provided by regulatory authorities voluntarily. The eMARS database represents the most detailed source of data considered in the development of the Natech database. Indeed, it provides a description of the accident that typically includes information such as the features of the installation, the substances involved, the causes, the consequences, and the emergency response.

- The MHIDAS database (Major Hazards Incident Data Service) [8,9]. It was managed by AEA Technology on behalf of the Health and Safety Executive of the United Kingdom. It was established in 1986 and it was dismissed in 2006. It collects records on accidents that occurred in the process industry and related sectors, such as the transportation and the storage of hazardous materials. The accidents contained in the MHIDAS database occurred in 95 different countries around the world. The quality of the data provided by the MHIDAS database is high. Indeed, each record provides an abstract of the accident, information on the cause-consequence chain of the events and details about the material and equipment involved.
- The TAD IChemE database (The Accident Database, Institution of Chemical Engineers) [10]. The database was populated in the period between 1997 and 2000 by the Institution of Chemical Engineers (IChemE) and it collects accidents that involve dangerous substances without limitations on the occurrence location. The TAD IChemE database is quite wide and contains over 10500 entries. The level of detail of the records available is slightly lower than those of the sources presented previously. Each record provides an accident description that includes information about the causes and the consequences of the events. However, the description of the equipment and the substances involved in the event are only provided for a limited number of records.
- The ARIA database (Analysis, Research and Information on Accidents) [11]. It is managed by the Bureau for Analysis of Industrial Risks and Pollutions (BARPI), and it collects records of events that have occurred since 1950 (only a limited number of records describe events that have occurred previously). The database provides information on events that affected or have shown the potential to damage health, public safety, or the environment. The ARIA database includes over 50000 records and every year about 1200 new entries are added. In principle, this source does not report limitations in the site where the event occurred. Despite this, around 85% of the records concern accidents that took place in France. The level of detail of the records present in the source is very varied and it can range from a brief description of the event to a complete description comparable to that included in the previously mentioned databases. Eventually, it should be noted that a part of the records is available only in French.
- The NRC database (National Response Centre) [12]. It was established in 1990 as part of the American National Response System and it is managed by the U.S. Coast Guard. The database collects events that involve the release of hazardous substances in the environment anywhere in the territories of the United States of America. The NRC database is the source with the higher number of entries. Differently from the previous sources, the entries are derived from voluntary calls of citizens that describe the spill to the Authorities. Thus, despite the high number of records that can be retrieved from this source, the descriptions given are concise, providing limited detail, and are not always accurate or verified.

- The CONCAWE database [13]. It is published within the "*Performance of European cross-country oil pipelines*" report of CONCAWE, a division of the European Petroleum Refiners Association. It is annually updated, and it collects records of events that resulted in a spill since 1971. This source only reports release events from specific pipelines. In addition, the CONCAWE database does not report a description of the event, but it only provides information about the service, the type and the part of the pipeline that failed.

As clearly understandable from the descriptions, the sources consulted are different from each other from various points of view, such as the geographical location considered, or the type of accidents included in the source. The diversity and variety of the sources should be accounted for when analysing the results of the database developed in the present work. Indeed, the original focus of each source influences the details available on the Natech events and the related results.

Certainly, other sources for the retrieval of chemical accident data are available, such as the Chemistry Safety Clearinghouse (CSC) [14], the Energy Institute Toolbox [15], the Failure Knowledge Database [16], the IOGP Safety Performance Indicators and Process Safety Events [17], the Process Safety Incident Database (PSID) [18], the ProcessNet [19], the Relational Information System for Chemical Accidents Database (RISCAD) [20], the Work Accident Map China Labour Bulletin [21], the ZEMA database [22], the FACTS database [23], and so on. Despite this, the database was based on the six sources described above, since the other databases mentioned suffer several criticalities, e.g., the Failure Knowledge Database and the Work Accident Map China Labour Bulletin were excluded as they do not allow a keyword search. Other databases are excluded as they are provided only in a language other than English such as the Chemistry Safety Clearinghouse (CSC) and the Relational Information System for Chemical Accidents Database (RISCAD). Moreover, databases that require a subscription for the consultation, such as the FACTS database, were also excluded. Eventually, it is worth mentioning that the eNatech database [24] managed by the European Commission's Joint Research Centre (JRC) was operational since 2012, a few years before the data retrieval process carried out for the development of the present database. For this reason, the number and quality of reports present in eNatech were limited and were not included in the present analysis.

After the selection of the sources, the next step of the data retrieval process was carried out, addressing the identification of records within the existing databases through a keyword search. Thus, a list of keywords was defined for the purpose. The list includes trivial words such as "*Natech*", "*Natural event*", and "*Natural disaster*". Because of the novelty of the discipline and the related terminology, the list was extended also to the natural events that may possibly cause a technological scenario, such as "*lightning*", "*flood*", and "*earthquake*". An excerpt of the complete list of keywords used is reported in Table 2.1. French translation of keywords was used to search the ARIA database.

Table 2.1. Excerpt of the list of keywords used for the search within the sources.

Keywords			
Natech	Tsunami	Wind	Tornado
Natural event	Volcanic activity	Extreme temperature	Typhoon
Natural disaster	Volcanic eruption	Cold wave	Tropical storm
Earthquake	Volcanic ash	Freeze	Flood
Ground movement	Fog	Ice	Flash flood
Ground settlement	Hailstorm	Snow	Wave action
Avalanche	Rain	Heatwave	Wildfire
Debris	Storm	Hot wave	Forest fire
Landslide	Thunderstorm	Cyclone	Land fire
Mudslide	Lightning	Hurricane	…

At the end of the data retrieval process, over 35000 records were gathered. These include a large variety of accident scenarios out of the scope of the present study. Thus, the events were further analysed to define whether to include them or not in the database, based on the criteria defined in the following section.

2.2.2 Inclusion criteria

As introduced previously, the records collected from the data retrieval process were further analysed. Specifically, three inclusion criteria were defined to identify events relevant to the purpose of the present work. The criteria are the following:

- The record should be classified as an accident, an incident or a loss of containment event.
- The record should be classified as a Natech event.
- The event should have occurred in the chemical and process industry or other industrial sectors that handle significant quantities of hazardous substances.

As for the first criterion, records were included in the present analysis if they were either accidents, incidents, or loss of containment events as defined in Table 2.2.

Table 2.2. List and definition of the events considered in the present work. Adapted from Ricci et al., 2021 [25].

Event	Definition
Accident	An event that may cause one or more fatalities or permanent major disabilities, and/or heavy financial loss [26].
Incident	An event that could cause considerable harm or loss such as a major health effect or injury, localized damage to assets and environment, or considerable loss of production and impact to company reputation [26].
Loss of containment	Events resulting in the release of material [5].

Concerning the second criterion, several different definitions are used in the literature for Natech events, as reported in Table 1.1 (see Section 1.1). Despite the scientific community does not agree with a single definition, all those provided are similar from a practical point of view. In the present work, the simple but exhaustive definition provided by the European Commission was adopted to include records in the database: "*Technological accident involving the release of, or the potential release of, hazardous materials, triggered by a natural event*" [27].

The third criterion was established to ensure the retrieval of a set of data relevant to the chemical and process industries. For this reason, events were included in the database only if they occurred in industrial sectors that handle relevant quantities of hazardous substances. Indeed, some sectors were disregarded from the analysis as they feature different safety standards and/or the technological scenarios differ from those typical of the chemical and process industry. For example, events that occurred in the nuclear industry, as well as those related to agricultural and mining activities were excluded from the database. Industrial activities considered in the present work were merged into 8 sectors based on the International Standard Industrial Classification of All Economic Activities [28]. The standard provides a complete list of industrial and productive activities and categories of these intending to support the reporting of statistics related to such activities. The industrial sectors included in the present work and the related definitions are reported in Table 2.3.

Table 2.3. List and description of the industrial sectors considered in the data collection. Adapted from Ricci et al., 2021 [25] *and Casson Moreno et al., 2018* [29].

Macro-sector	Description
Chemical & Petrochemical	Chemical activities, including pesticide production, pharmaceutical industry, and production of basic chemicals. Petrochemical activities, including refineries.
Storage & Warehousing	Sites where chemicals are stored in appointed equipment (i.e. storage tanks) and storage buildings (warehouses/depots).
Power production	Power production plants using hydrocarbons (thermal power stations). Nuclear power plants were not included in the present analysis.
Bioprocesses	Treatment of organic waste and waste fermentation juices; food industry.
Water treatment	Treatment of water for industrial and domestic purposes (excluding bioprocesses-related waters and slurries).
Transportation	Transportation of hazardous materials via road, rail and water.
Pipeline	Oil and gas transportation via pipelines.
Manufacturing	Metalworking, textile industry, and activities related to the automotive sector where hazardous substances are used.

It is worth mentioning that no limitations in the year of occurrence of the events were introduced. However, only events that occurred before December 2018 were considered since the data retrieval process was concluded at the beginning of 2020. Indeed, sources typically require at least one year before making the records available. Thus, the time gap was chosen to ensure that at least the majority of the events that occurred in the last solar year considered were included.

Eventually, particular attention was devoted to avoiding the inclusion of duplicate records. This was necessary due to the high number and variety of the sources consulted. To this aim, specific checks were based on the date and location of the event, the type of industrial activity, the outcome, and the substance and equipment item involved in the event. Noteworthy, when duplicate records were found, all information provided by the sources were merged. Records were then attributed to the source that contain most of the information retrieved.

2.2.3 Database structure

The records collected and included in the dataset were then organised in a database. The structure of the database is shown in Figure 2.2. The database consists of 7 main sections: general information, temporal, location, triggering natural event, technological scenario, substance, and severity.

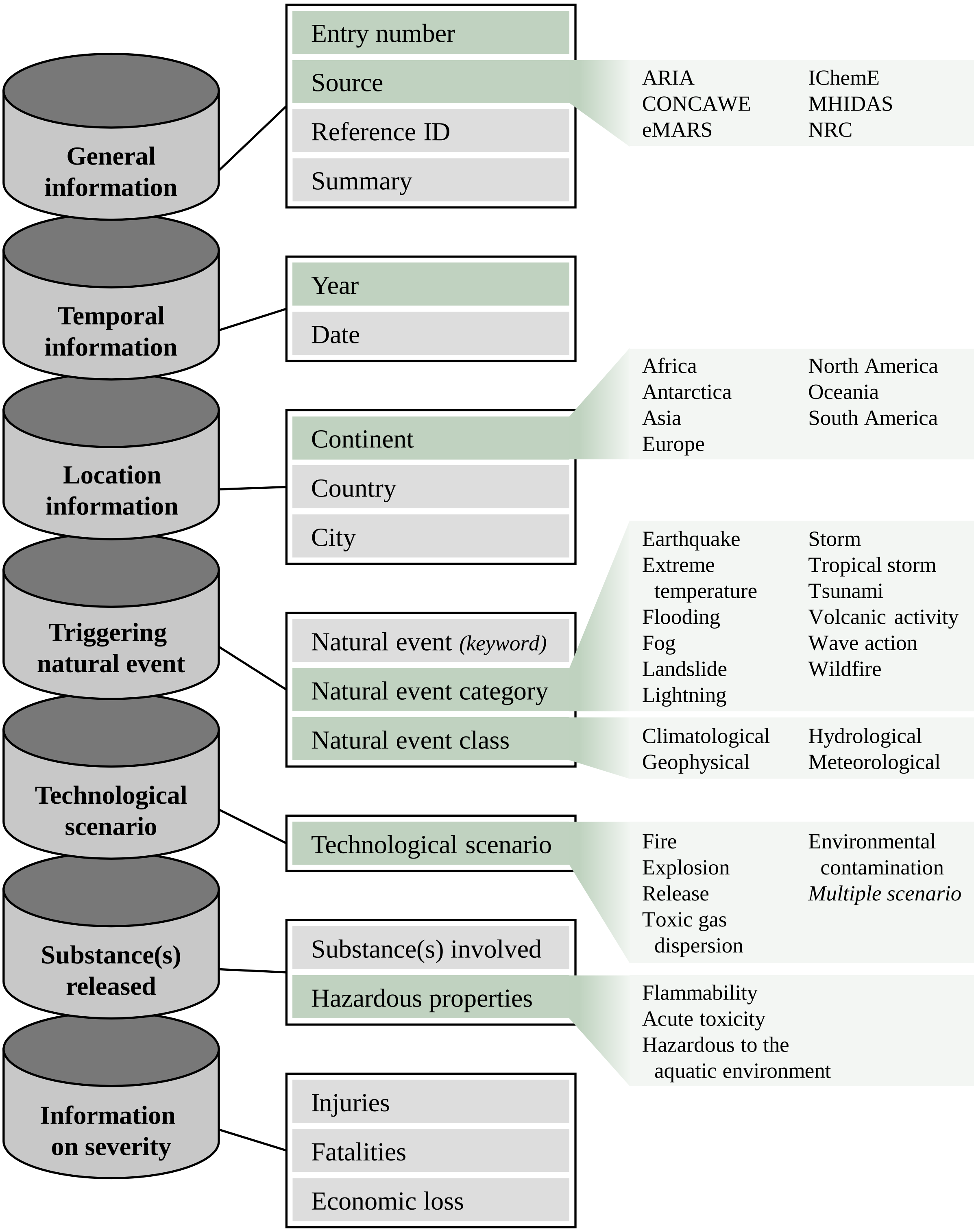


Figure 2.2. Structure of the database.

In the "*general information*" section, the entry number in the database, the source from which the record is collected, the reference ID in the source and a summary of the event are reported. The "*temporal*" section contains the year of occurrence of the event together with the date when available. Concerning the "*location*" section, it provides information on the place where the event occurred, specifically the continent, the country and the city when the information is provided in the source.

The "*triggering natural event*" section contains information on the natural events that caused the Natech accident. It reports the specific natural event, which represents also the keyword used to retrieve the record in most cases. Being the keywords used elevated in number and variegated, a classification of the natural events was required to make the analysis more consistent. Natural events were thus merged into 12 categories and then grouped into 4 classes according to the terminology provided by the EM-DAT glossary [1]. Figure 2.3 reports a schematic representation of the classification used in the present work and Table 2.4 defines the 4 classes considered. The category of each natural event and the related class is also reported in the "*triggering natural event*" section of the database.

Table 2.4. List and definition of the macro-categories of natural events adopted in the present study. Adapted from the EM-DAT glossary [1].

Term	**Definitions**
Geophysical	A hazard originating from solid earth. This term is used interchangeably with the term geological hazard.
Meteorological	A hazard caused by short-lived, micro- to mesoscale extreme weather and atmospheric conditions that last from minutes to days.
Hydrological	A hazard caused by the occurrence, movement, and distribution of surface and subsurface freshwater and saltwater.
Climatological	A hazard caused by long-lived, meso- to macro-scale atmospheric processes ranging from intra-seasonal to multi-decadal climate variability.

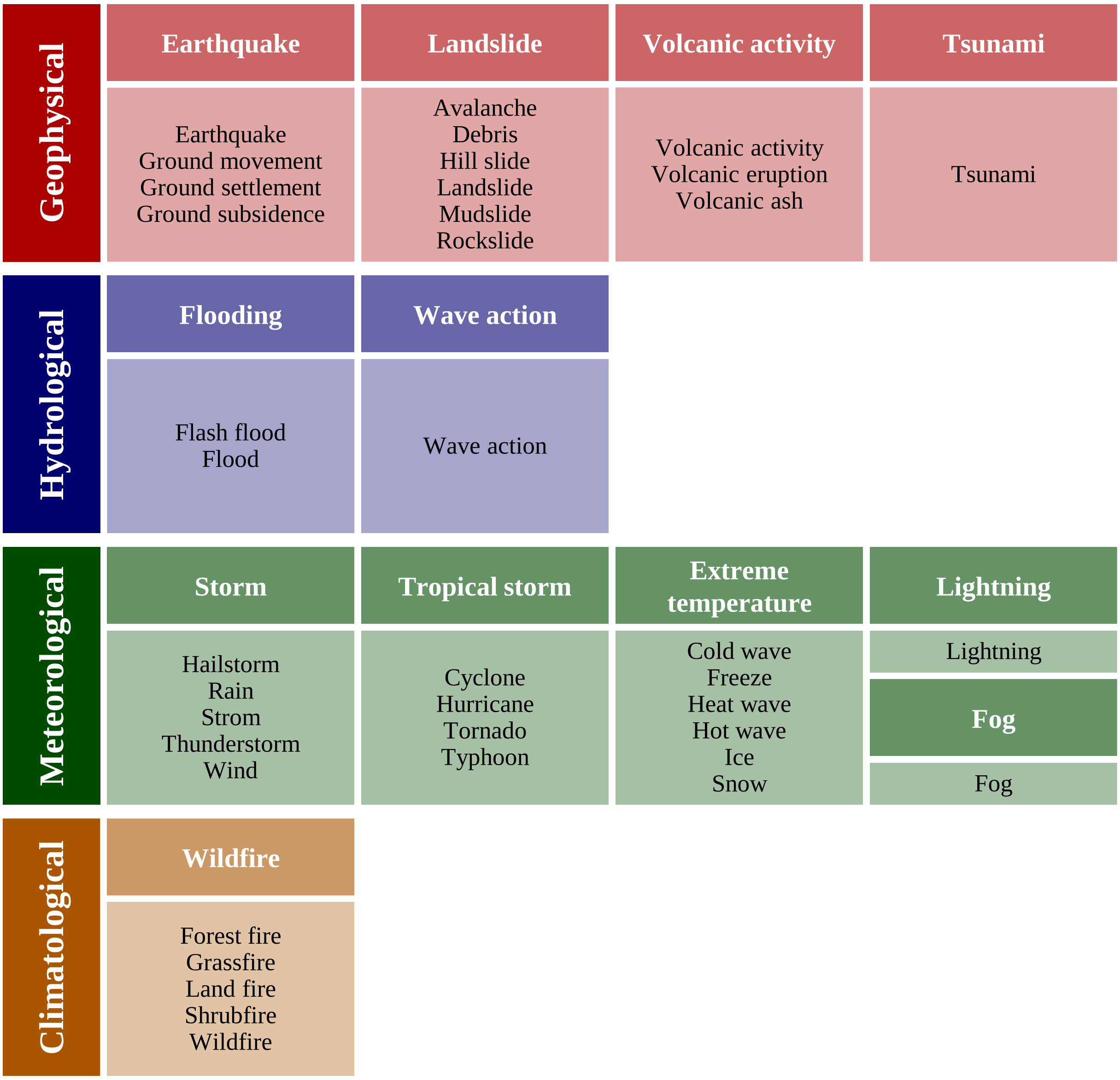


Figure 2.3. Categories and classes of natural events triggering technological scenarios based on the definitions given by the Centre for Research on the Epidemiology of Disasters [1] *and reported in Table 2.4.*

The "*technological scenario*" section reports information on the outcome that resulted from the event. Here, 5 main scenarios were considered: fire, explosion, toxic gas dispersion, environmental contamination, and release with no further consequences. The definition of each outcome is reported in Table 2.5. Eventually, the cases in which more than one scenario occurred in the event are referred to as "*multiple scenarios*" in the following.

Table 2.5. List and definition of technological scenarios present in the database.

Scenario	Definition
Fire (F)	An uncontrolled combustion process characterized by the emission of heat and smoke. Includes all types of industrial fires, i.e. pool fires, flash fires, jet fires and fireballs [30].
Explosion (E)	A sudden release of energy that causes a blast wave [30]. Includes all types of industrial explosions, i.e. unconfined and partially confined gas and vapour explosions (VCE), confined explosions, and mechanical explosions [31].
Toxic gas dispersion (TGD)	The dispersion of a toxic substance in the air [32].
Environmental contamination (EC)	Contamination of surface waters (rivers, lakes, seas, ...) or of the aquifer by substances harmful to the aquatic environment [32].
Release with no further consequences (R-NFC)	The release of a liquid or gas from its containment [30], in quantities and concentrations that have no short-term potential consequence for persons and the environment.

The “*substance*” section provides information on the substances released in the event. Together with the substance, the section reports also its hazardous properties. The classification of the hazardous properties was done according to the Globally Harmonized System [33] into three categories: flammable substances, acutely toxic substances, and substances hazardous to the aquatic environment. It is worth mentioning that a substance may be classified according to more than one hazardous category, and the combination of all these is considered in the present work. Similarly, when an event involves more substances, all the related hazardous categories are considered.

The last section of the database is devoted to the “*severity*” of the events. Specifically, it contains information on the damages to humans and the economic loss of the event. As for humans, data on the number of injuries and fatalities are collected when available in the source. Concerning the economic loss, the values reported in the database are prone to large uncertainty, both connected to the initial estimation provided by the source and the exchange rate used to perform the analysis in a single currency (specifically, euros).

Part of the work dedicated to the definition of the database structure was devoted to the harmonisation of the main field to support the following analysis. Thus, the database is composed of both itemized fields and free text entries. The latter group includes all the items for which the information may change substantially for each event, such as the summary. On the contrary, itemized fields were used to standardise the input data, e.g. with respect to the triggering natural event and the technological scenario. Figure 2.2 reports in grey the free text entries and in green the itemised ones. In addition, the figure also provides the possible entries for each itemised field.

2.3 Statistical analysis of the database

In the present section, results deriving from the statistical analysis of the developed database are reported. The analyses performed are related to the temporal and geographical distribution of the records collected, the share among the natural phenomena that caused the events, the technological scenarios that occurred and the substances involved in the event. Eventually, data on the severity of the events in terms of damages to humans and economic loss are provided.

2.3.1 Data sources

The data retrieval process and the following refining procedure based on the inclusion criteria led to the collection of 9100 records that were included in the database. Figure 2.4 shows the share among the sources of the collected records. As can be observed from the figure, the NRC database represents the main source of information for the present study providing over 85% of the total records collected (7752 records), followed by the ARIA database (1028 records, 11.3% of the total). Hence, less than 4% of the total number of collected records is obtained from the remaining sources. Despite the lower incidence on the database, it is worth mentioning that sources such as the eMARS and the TAD IChemE database provide records with a higher level of detail among all the sources consulted, as already stated in Section 2.2.1. Thus, information retrieved from these databases is very useful to characterise Natech events.

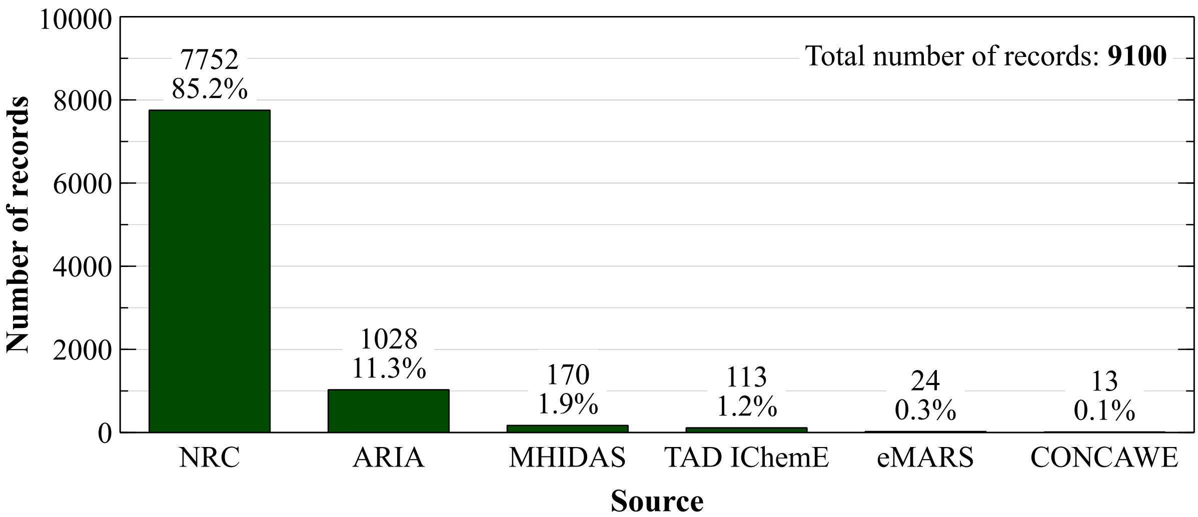


Figure 2.4. Share among the sources of the collected data.

The share among the source agrees with those of previous databased developed related to Natech accidents [34,35]. Indeed, even in other cases where the NRC database has been consulted together with other sources, this has always proved to be the major source of information. Furthermore, the high number of records collected from the NRC database is not surprising, as even more records have been obtained in previous work that focused only on this source [36,37]. Noteworthy, the lower number of records considered in this work from the NRC database is due to the more restrictive inclusion criteria defined in Section 2.2.2 compared to those used in previous studies.

Eventually, the percent of Natech events present in each of the sources was calculated, and it ranges from 0.9% to 2.4%. Overall, events collected represent 1% of the total available records in all the databases consulted.

2.3.2 Distribution over time and space of Natech events

The dataset collected covers a period of almost 70 years. Figure 2.5 shows the quinquennial time trend of the records. The influence of the different sources on the overall dataset is clear. Specifically, the significant contribution of the NRC database as a source of information is clearly shown when comparing Figure 2.5-a and Figure 2.5-b, which report the time trend considering all the sources consulted and the one excluding the NRC database. Looking at the first panel, the number of records grows considerably starting from 1990, which corresponds to the establishment of the NRC. An almost constant number of records was collected per year from this source (around 250 records per year). Indeed, only a few peaks are present in the trend, and they are related to the periods 1990-1994 and 2005-2009. These five-year periods were characterised by the occurrence of several high-magnitude natural events in the USA, which is the geographical location of the records collected from the NRC database. For instance, the Atlantic hurricane season of 1990 was the most active one since 1969 [38]. Moreover, the Northridge earthquake (moment magnitude 6.7 on the Richter scale) hit the City of Los Angeles and its surrounding area causing several accidents in industrial facilities [39]. Eventually, several high-magnitude hurricanes occurred in the period 2005-2009 such as Katrina and Rita in 2005 [40–42] and Ike and Gustav three years later [43].

As suggested by the features of the NRC database, the time trend evaluation was performed also excluding this source from the analysis, as reported in Figure 2.5-b. The figure shows an increasing trend of Natech events over time, especially in the last 50 years. The trend may have multiple causes, such as the growing number of records available in the sources, the increasing number of natural events, and the rising industrialisation. Nevertheless, the relevance of possible interaction between natural hazards and industrial sites is confirmed by the increasing number of Natech events over the years.

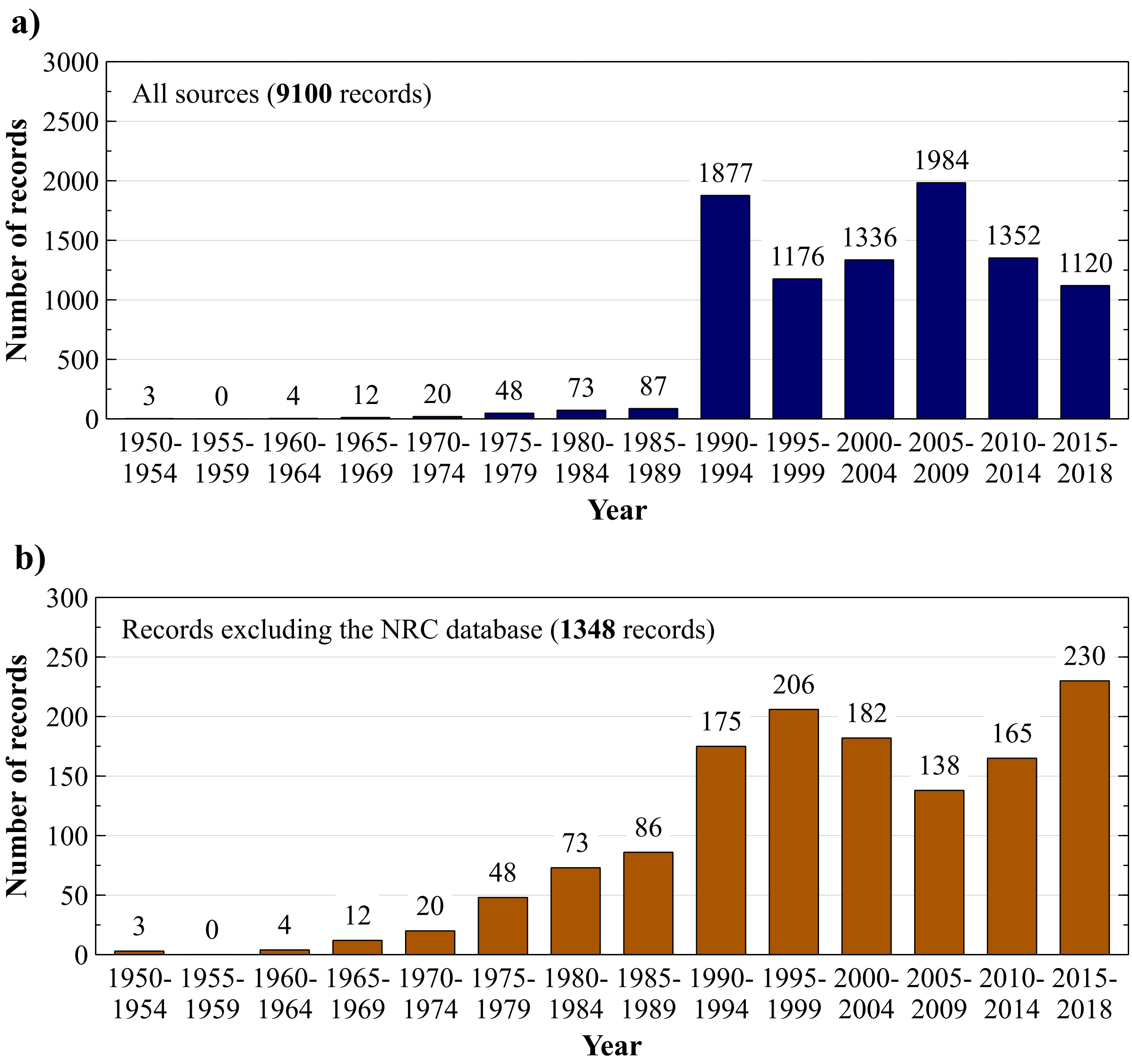


Figure 2.5. Quinquennial time trend of the Natech events collected in the database considering (a) records from all the sources and (b) excluding records from the NRC database.

Figure 2.6 reports the geographical distribution by continent of the collected records. North America (7925 records, 87.1% of the total) and Europe (897, 9.9%) seem to be the two continents most affected by Natech events, representing together over 97% of the entire dataset. These data however should be interpreted also in the light of the sources consulted. Indeed, the specific features of each source should be taken into account when analysing the results, as already mentioned above. Specifically, the records provided by the NRC database are related to events that occurred only in the United States of America. Thus, an elevated number of records for North America was expected, specifically for the USA, since the NRC database is the main source of records in the dataset (see Figure 2.4). Similarly, the ARIA and the eMARS databases represent a wide source of information for events that occurred mainly in Europe. Nevertheless, the ratio between the records collected from these sources and those from the NRC database may explain the lower incidence of events that occurred in Europe with respect to North America.

Eventually, a limited number of the collected events occurred in the other continents. This low incidence can be attributed to several factors. For example, a probable underreporting of events that occurred in these areas should be considered in the consulted sources, as can be the case in some industrialised countries in Asia. Moreover, the low industrialisation of some areas makes them less prone to the development of industrial accidents, as in the case of some areas in Africa. Lastly, it is worth mentioning that no sources specific to these countries are considered for the development of the database.

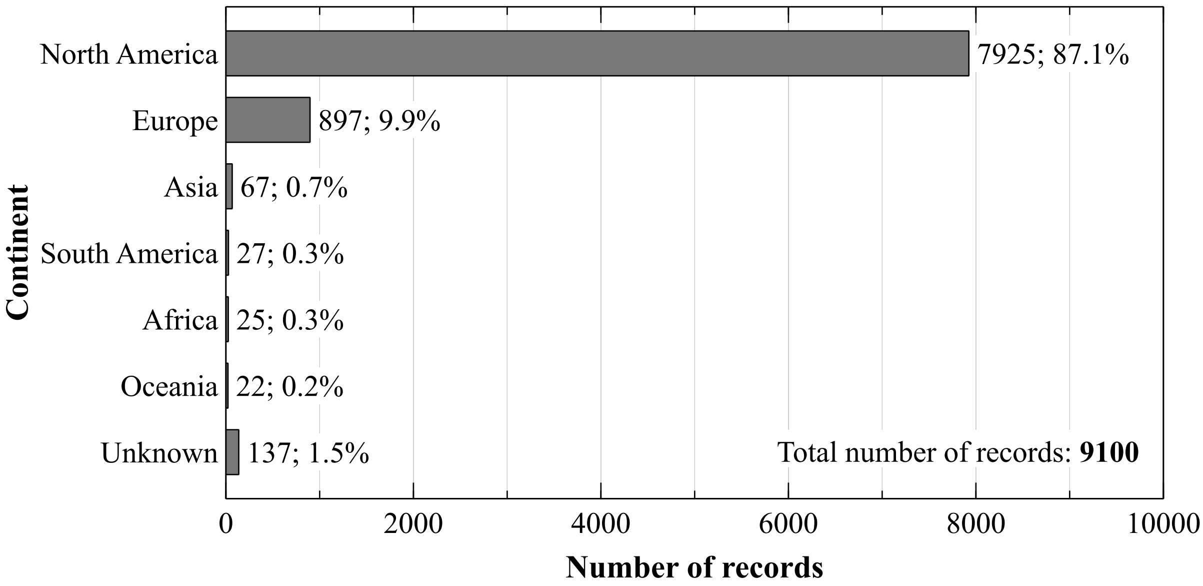


Figure 2.6. Location by continent of the records collected in the database.

A more detailed geographical distribution of the collected records is provided per country in the map reported in Figure 2.7-a. The same figure (Figure 2.7-b) shows also the worldwide distribution of natural disasters according to the data provided in the EM-DAT database developed by the Centre for Research on the Epidemiology of Disasters [1]. According to the source, "*disasters*" are defined as events that verify at least one of the following conditions: fatalities equal to or higher than 10, affected individuals equal to or higher than 100, the deflation of the state of emergency, and the need for international assistance.

Comparing both panels of Figure 2.7, a correlation between the number of Natech events and those of natural disasters may be observed. Indeed, countries most affected by natural disasters are also those in which a higher number of Natech events was recorded, even considering the geographical areas for which a limited set of data is available for Natech events. Additional consideration can be provided considering the absolute values of the events. Indeed, the ratio between Natech events and natural disasters in North America is large (around 3.5). A possible explanation of this value may be found when considering that several states in the USA are impacted by hurricanes. These natural disasters are characterised by a high magnitude, and they typically affect extended areas. Thus, several industrial sites may be affected by a single hurricane, possibly generating a multitude of Natech events [41,42,44,45]. Differently, when considering Europe, the ratio between Natech events and natural disasters is considerably lower (around 0.5). Again, countries in coastal areas seem to be more affected, possibly due to the higher industrialisation of these countries. For the other geographical areas, the ratio was not statistically significant due to the limited number of Natech events that were collected (see Figure 2.6).

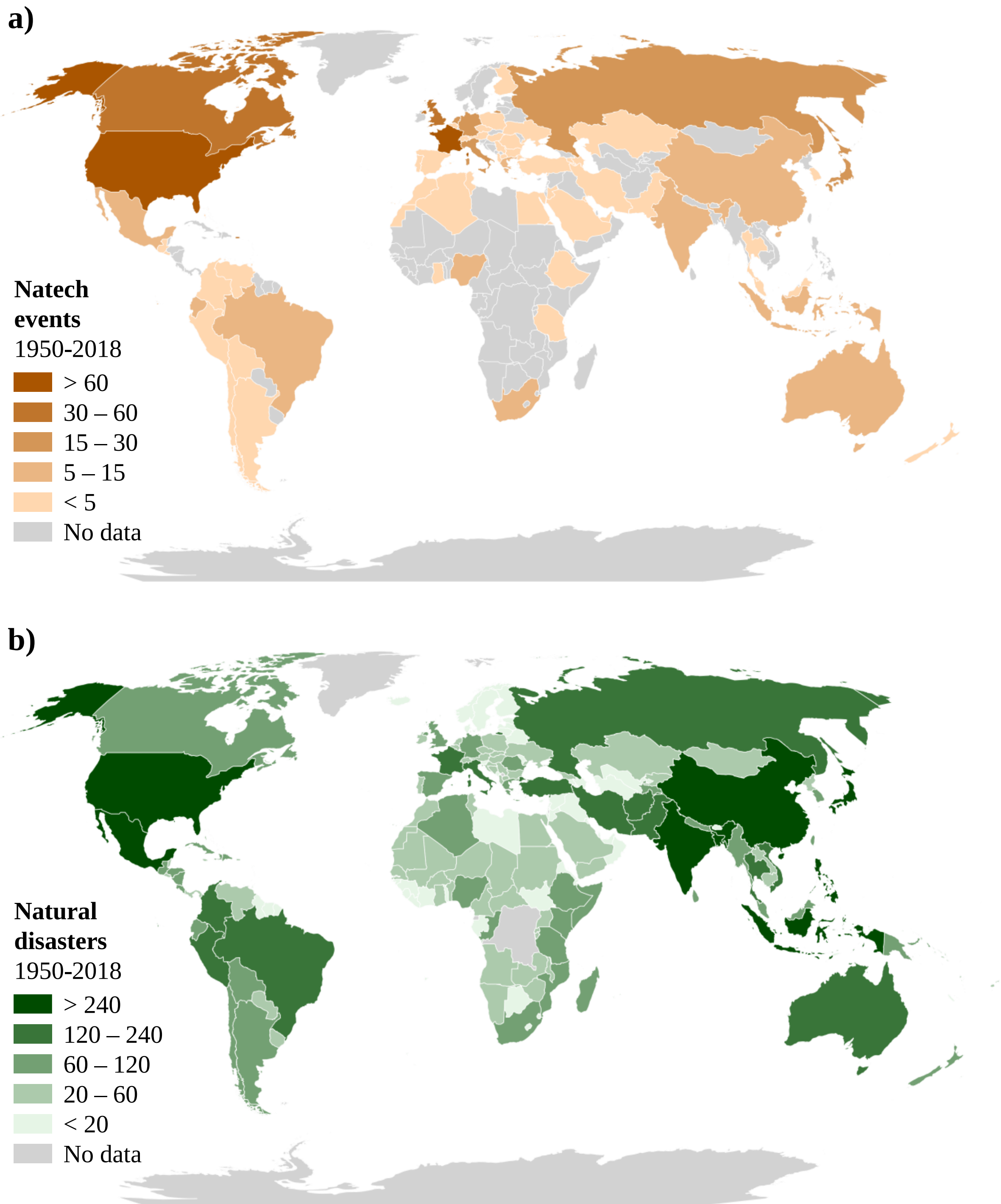


Figure 2.7. Worldwide map of (a) Natech events collected in the database and (b) natural disasters recorded in the EM-DAT database [1]. *The period considered ranges from 1950 to 2018.*

The United States of America and the countries of Europe are those for which a wide set of records was collected in the database, as already discussed when introducing Figure 2.6 and Figure 2.7-a. Given the significance of these countries, an additional analysis was performed. Specifically, an estimation of the trend of Natech events normalised on the number of industrial sites was carried out over time. The trend was calculated by dividing the number of Natech events by the number of productive industrial activities year by year. An estimation of the number of sites was retrieved from the UNIDO Statistics Data Portal [46], which provides yearly information for the period from 2000 to 2017. Thus, the trend calculation was limited to the same period. Eventually, Natech events related to the "*Transportation*" sectors present in the database (see Table 2.3) were excluded from the analysis.

The trend of the Natech events normalised on the number of industrial sites is reported in Figure 2.8 for the United States of America (panel a) and Europe (panel b). Considering the USA, the trend appears quite constant, and an average frequency of Natech events can be estimated at around $2.3 \cdot 10^{-3}$ events/year/site representative for the period considered. Noteworthy, two peaks are present, and they are probably associated with the hurricanes Rita and Katrina (2005) and hurricanes Gustav and Ike (2008). A quite different situation can be observed for Europe, where the average frequency of Natech events per site is around $3.5 \cdot 10^{-5}$ events/year site in the period 2000-2017, two orders of magnitude lower than the value obtained for the USA. Despite this, it is important to highlight that a slightly growing trend is present in Europe, and the frequency increased by a factor of approximately 2.5 between the beginning and the end of the period. This result raises some concern about the possible growing occurrence of Natech events in Europe in future years.

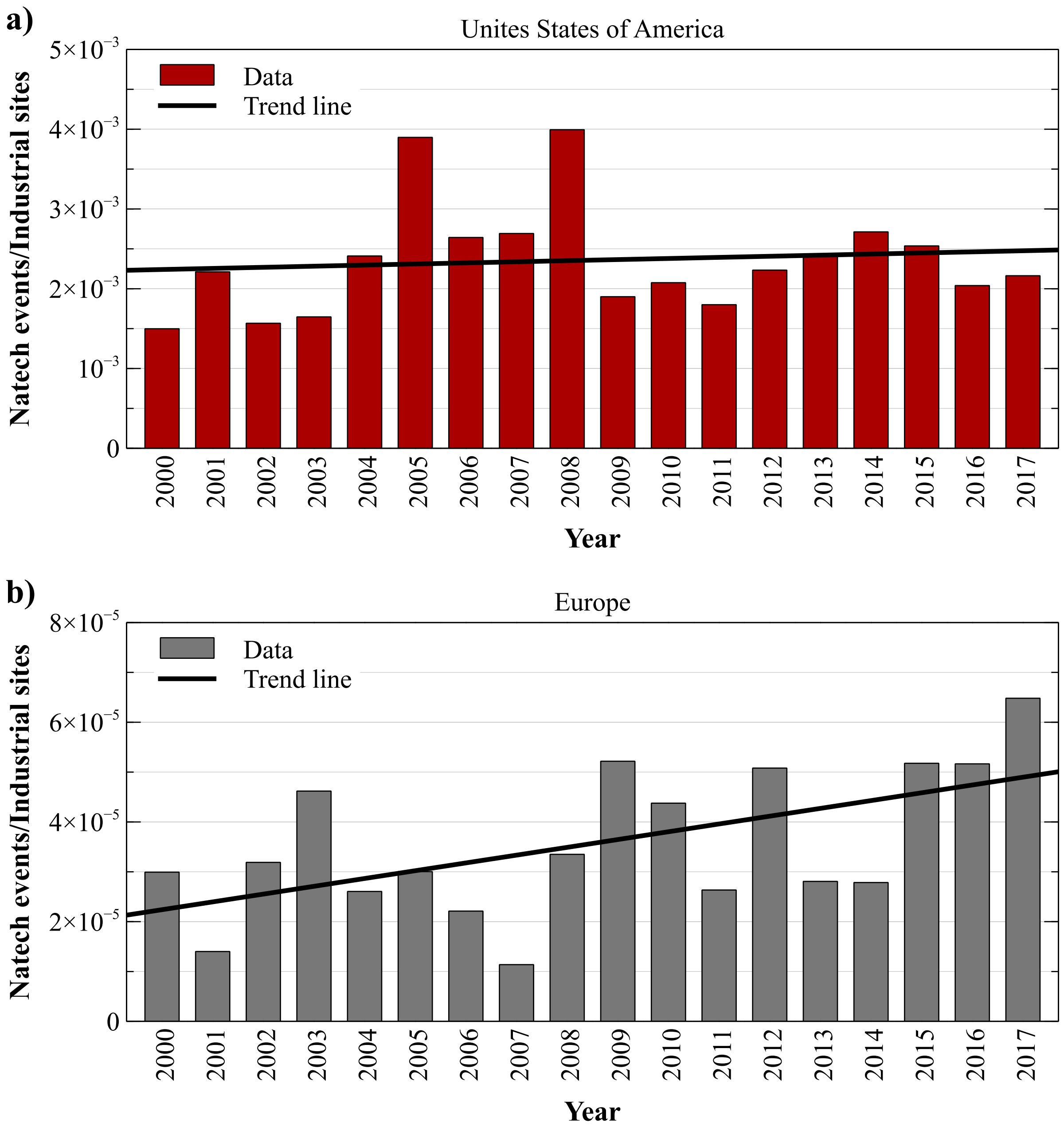


Figure 2.8. Natech events per industrial site in the period 2000-2017 for (a) the United States of America and (b) Europe.

2.3.3 Natural phenomena triggering Natech events

The present section aims at providing details on the natural phenomena that caused the Natech events collected in the database.

Firstly, the analysis focused on the class of natural phenomena as defined and classified in Table 2.4 and Figure 2.3. The share among the class of natural phenomena is reported in Figure 2.9 (orange bars). As can be observed, meteorological events caused most of the records collected in the database, with

7866 entries that represent over 86% of the total. Hydrological and geophysical phenomena triggered a considerably lower number of events, less than 10% (895 records) and 4% (336 records) respectively. Even if the percentage in the database is low, events included in hydrological and geophysical classes are typically characterised by greater magnitudes. Thus, consequences related to the technological scenarios triggered by these phenomena are typically serious. Eventually, climatological phenomena (i.,e, wildfires) caused only 3 events. Despite the low incidence in the database, Section 1.2 reported that the worldwide number and magnitude of wildfires are increasing in the last decades. This is also promoting the condition for the development of technological scenarios induced by wildfire. Thus, climatological events such as wildfires are becoming a crucial aspect in the framework of Natech risk. Indeed, Section 2.6 of the present chapter provides a focus on wildfire-induced accidents collected in the database.

Figure 2.9 also shows the share among the class of natural disasters according to the data provided by the EM-DAT database [1]. Comparing the information, it is worth highlighting that geophysical and hydrological phenomena have a lower incidence on the overall number of Natech events than those of natural disasters. On the contrary, meteorological events seem more prone to cause Natech events, and these can be attributed to at least two factors. On the one hand, meteorological events include events such as hurricanes and tropical storms, which may lead to several Natech accidents considering a single natural event as already explained in the previous sections. On the other hand, the meteorological class is also made up of natural phenomena that sometimes may feature moderate magnitude (such as lightning, storm, and wind), which does not allow their inclusion in the EM-DAT database according to the definition used for natural disaster (see Section 2.3.2). However, these natural phenomena may still lead to the development of industrial accidents, confirming that not only high-magnitude natural disasters cause Natech events but also those of moderate magnitude [3,47–49]. In general, the results of this analysis suggest that the chemical and process industry may be particularly vulnerable to short-term (minutes, days) medium-scale weather events.

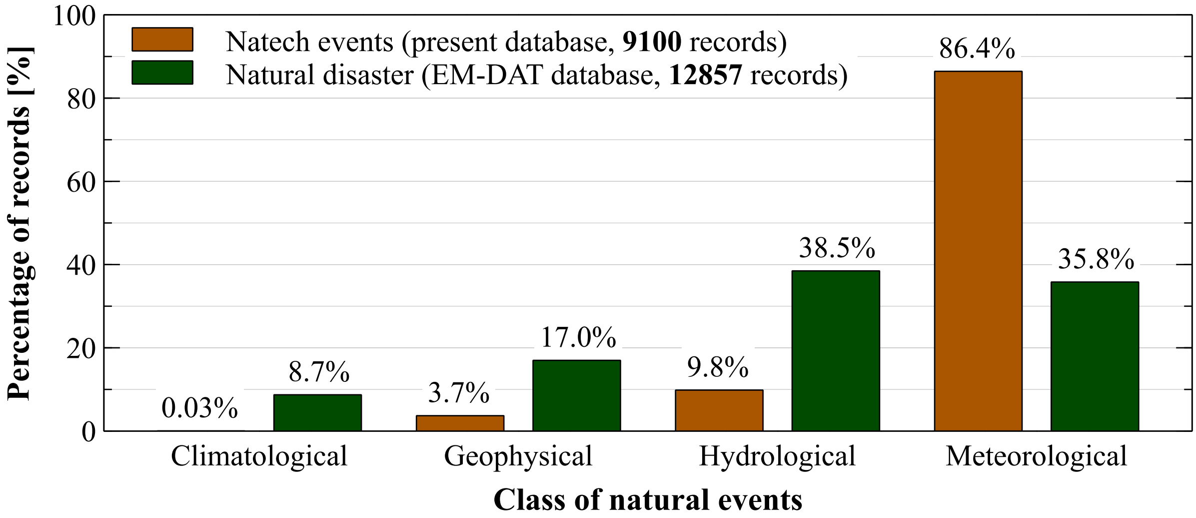


Figure 2.9. Distribution of Natech events (orange bars) and natural disasters (green bars) as a function of the class of natural phenomena (see definition in Table 2.4). Data on natural disasters are retrieved from the EM-DAT database [1].

More in detail, Figure 2.10 shows the number of Natech events caused by each category of natural phenomena considered in the present study (see Figure 2.3). As might be expected, the first four categories of natural phenomena all belong to the class of meteorological events. Specifically, storms triggered more than half of the collected records (4578 records, 50.4% of the total), followed by tropical storms (1135, 12.5%), extreme temperature (1113, 12.2%), and lightning (1024, 11.3%). A considerably lower percentage is then associated with floods (788, 8.7%) and earthquakes (166, 1.8%). Although the lower influence in the database, earthquakes and floods are natural events particularly critical, as they can lead to severe consequences and escalation scenarios [2,3,50,51]. Indeed, most of the attention was dedicated to the Natech accidents caused by these natural events in the past decades [52–56]. Eventually, other causes of the Natech events retrieved in the database are landslide (164, 1.8%), wave action (107, 1.2%), fog (16 records), tsunami (5 records), wildfire (3 records), and volcanic activity (1 record).

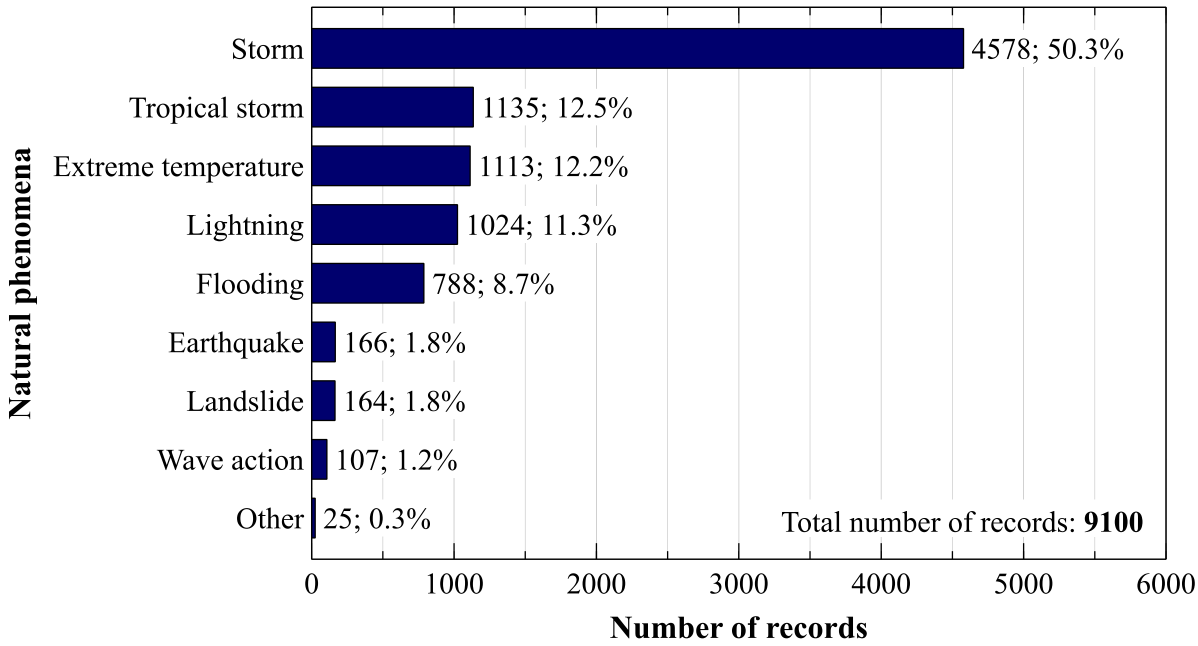


Figure 2.10. Distribution among the natural phenomena that caused the Natech events. "Other" includes Wave action, Volcanic Activity, Tsunami, Fog, and Wildfires.

2.3.4 Technological scenarios

A general overview of the technological scenarios resulting from the Natech events collected in the database is presented in the following.

Figure 2.11 reports the distribution among the technological scenarios considered in the present study (see Table 2.5 for the definition). Two technological scenarios were found to be almost equally probable and they alone account for over 89% of the total: the release with no further consequences ("*Release NFC*" in Figure 2.11, 4119 records, 45.3% of the total) and the environmental contamination (3970 records, 43.6% of the total). As for the remaining 11% of the records, events resulted in fires (826, 9.1%), multiple scenarios (101, 1.1%) and explosions (73, 0.8%). Only in a marginal number of events, a toxic gas dispersion has occurred (11, 0.1%). Eventually, the combination of fire and explosion represents 96% of the multiple scenarios (97 records).

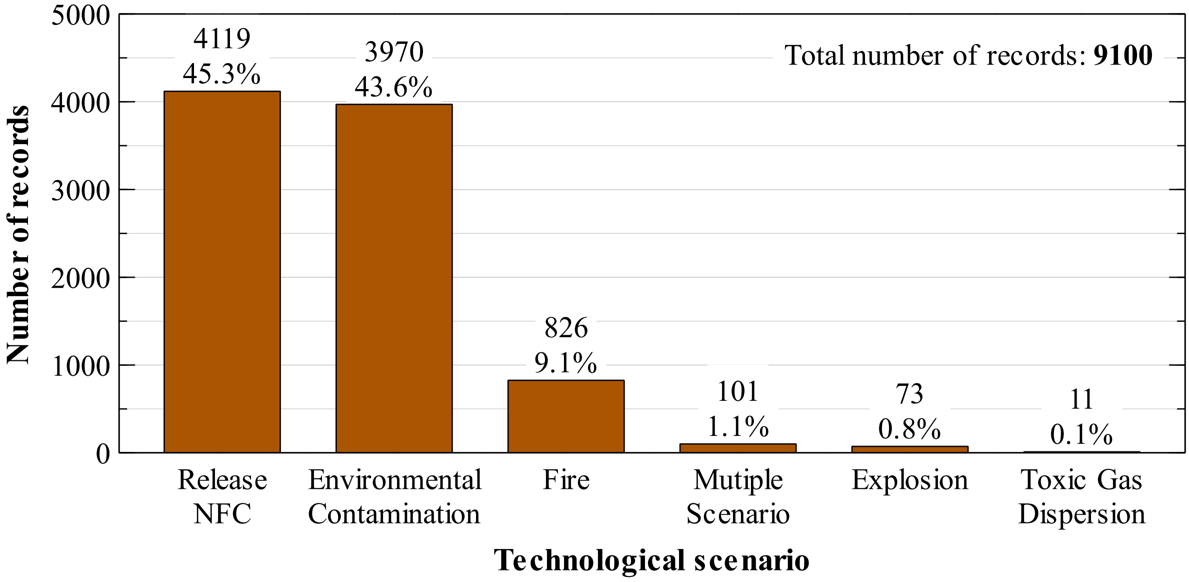


Figure 2.11. Technological scenarios occurred in the Natech events included in the database. Release NFC: Release with no further consequences.

As introduced at the beginning, the present section aims at providing an overview related to the technological scenarios. Besides the importance of an aggregated analysis, Section 2.4 of the present work is entirely devoted to the detailed analysis of the technological scenarios as a function of the triggering natural phenomena and the type of substances released in the Natech events.

2.3.5 The severity of Natech events

In the present section, the severity of the collected Natech events is discussed in terms of economic losses and damages to humans. Noteworthy, the number of records reporting information on the impact on humans and assets is considerably lower than the overall number of collected records. The different level of detail available in the consulted sources, as anticipated in Section 2.2.1, is the main cause of the lack of information related to these aspects. This means that damages to humans and assets may have occurred also in accidents for which the information is not provided in the sources. Thus, the results obtained somehow represent an underestimation of the real consequences on humans and assets of Natech events.

Information on the economic loss was reported in 151 records. As introduced in Section 2.2.3, data on economic losses are affected by a large uncertainty. Thus, the analysis was performed by merging the economic losses into 5 classes, which differ from each other by the order of magnitude of the loss. Then, the probability of economic loss for each range was evaluated and the results are reported in Figure 2.12

considering four different cases: *(a)* the entire dataset, *(b)* geophysical events, *(c)* hydrological events, and *(d)* meteorological events. The economic damages related to Natech triggered by hydrological and meteorological events show a trend like those obtained considering the entire dataset, with a slightly higher probability associated with the low to moderate ranges of losses. Geophysical phenomena, instead, resulted in an average higher probability of economic damages, especially when the range related to the greatest loss is considered (more than 10 million €). The presence of earthquakes within the geophysical events may easily explain the trend, as they are considered severe natural events prone to the development of multiple simultaneous failures as demonstrated by past accidents [50,51].

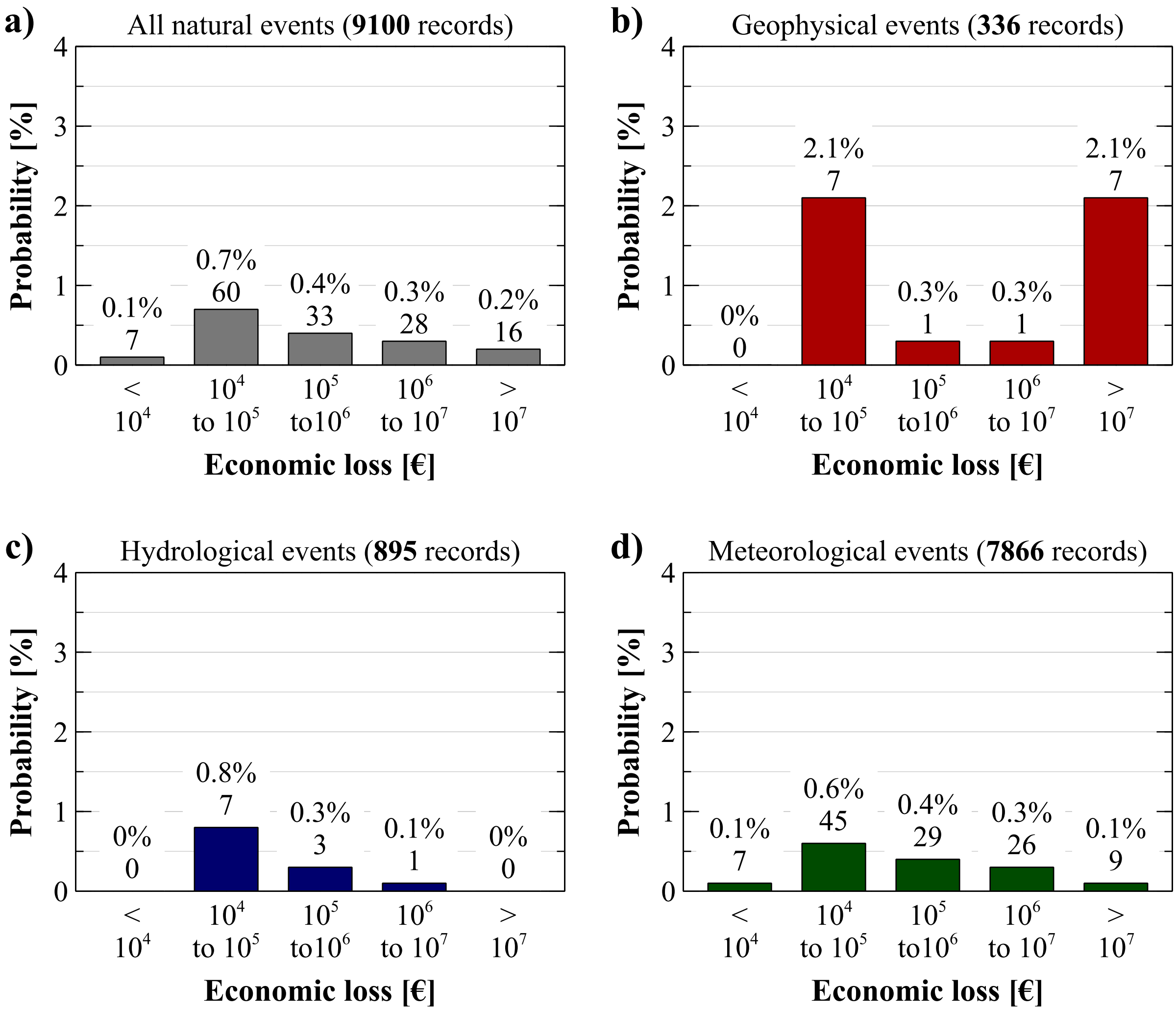


Figure 2.12. Probability of occurrence of economic losses considering (a) the entire dataset, (b) geophysical events, (c) hydrological events, and (d) meteorological events. Probabilities are calculated considering the number of records collected for each class under analysis.

The number of records which provides information on damages to human was slightly higher (210 records) and a total of 1734 fatalities and 7320 injuries were reported. Similar to the case of economic damages, the probability of occurrence of impacts on humans was performed based on a simplified severity scale. Thus, four classes were defined: "*one injury*", "*multiple injuries*", "*one fatality*", and "*multiple fatalities*". To perform a conservative estimation, records which report both injuries and fatalities were assigned to the related class of fatalities, as it represents the worst scenario. Figure 2.13 shows the probability of occurrence of damages to humans considering the same four cases defined in the economic damage evaluation. Comparing Figure 2.12 and Figure 2.13, a similar trend can be observed for both damages to humans and economic losses. Here again, geophysical events show a higher probability than all the other classes of natural phenomena.

Eventually, the analysis related to climatological events is not reported as it is not relevant from a statistical point of view due to the low number of records collected for this class. Despite this, among the 3 records collected for wildfire, one accident reported 12 injuries and another one reported an economic loss of around 45000€. Thus, consequences that may arise from industrial accidents triggered by wildfire can be relevant.

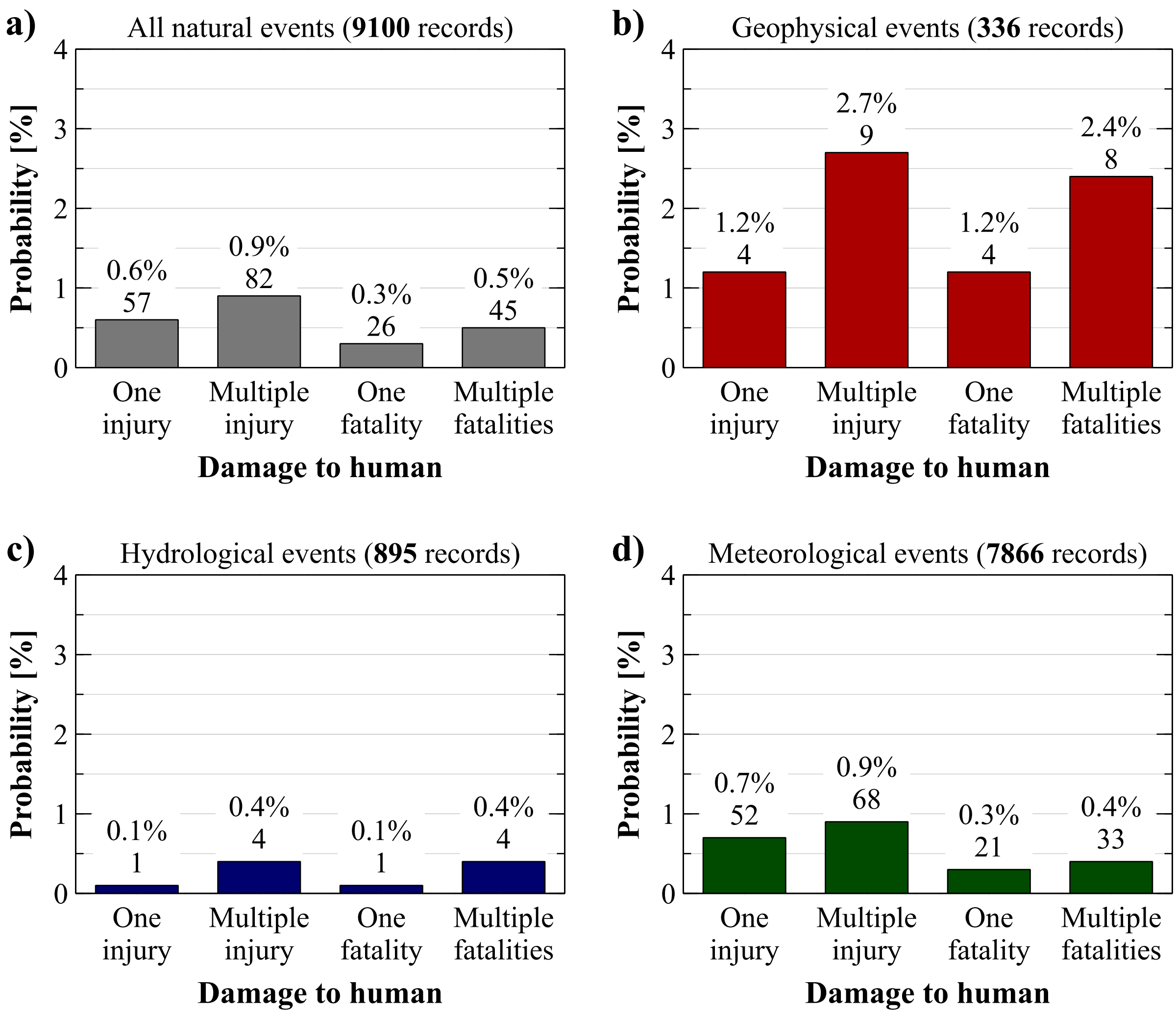


Figure 2.13. Probability of occurrence of damages to humans considering (a) the entire dataset, (b) geophysical events, (c) hydrological events, and (d) meteorological events. Probabilities are calculated considering the number of records collected for each class under analysis.

2.3.6 Hazardous substances involved in Natech events

In this section, an overview of the substances involved in the Natech events is presented. As for the case of the severity analysis, the lack of information in the sources did not allow to perform the analysis for the entire database. Despite this, a dataset of 7476 records provided sufficient information for the identification of the substances involved and the related hazardous properties.

A total of over 670 hazardous substances were identified in the dataset. Table 2.6 reports an excerpt of the substances involved in at least 100 records of the dataset and the related number of occurrences.

Table 2.6. Excerpt of the substances involved in at least 100 records of the dataset, number of occurrences and the related percentage.

Substance	Number of records [-]	Percentage [%]
Crude oil	1734	19.1%
Fuel oil	1153	12.7%
Oil *(not better specified)*	807	8.9%
Natural gas	460	5.1%
Lubricating oil	237	2.6%
Hydraulic oil	189	2.1%
Ammonia	186	2.0%
Motor oil	185	2.0%
Waste oil	167	1.8%
Benzene	117	1.3%
Hydrocarbons *(not better specified)*	103	1.1%

Then, the substances were classified as a function of hazardous properties according to the Globally Harmonised System (GHS) introduced by the United Nations [33]. As introduced in Section 2.2.3, three main hazardous categories were accounted for in the present study: flammability, acute toxicity, and substances hazardous to the aquatic environment. The analysis was limited to this set of categories since they allow to cover the majority of substances present in the chemical and process industry. Within the dataset, some events involved more than one substance (453 records), while in a relevant number of events a substance classifiable according to more than one category was released (5758). In both cases, all the hazardous categories were considered in the analysis, as introduced in Section 2.2.3. Overall, substances at least classified as flammable are the most present in the database, and they were involved in 7105 records. A slightly lower incidence is instead attributed to accidents involving substances classified at least as hazardous to the aquatic environment, which was released in 6109 records. Eventually, substances categorized at least as acute toxic were involved in 1758 records.

Considering the above-mentioned hazardous categories, seven possible combinations of them can be used to classify a record. Thus, it is important to analyse the distribution of these combinations among the dataset, and the result is shown in the Venn diagram reported in Figure 2.14. As can be noticed, around 18% of the records involved a substance or more substances with a single hazardous property, this being mainly the flammability (1053 records over 1352). A similar percentage is associated with the case in which all three hazardous properties are involved in the event (18.3%). In addition, flammability and eco-toxicity (substances hazardous to the aquatic environment) were involved in a wide set of records, around 61% of the total. Eventually, a marginal percentage is associated with the other combinations of hazardous properties.

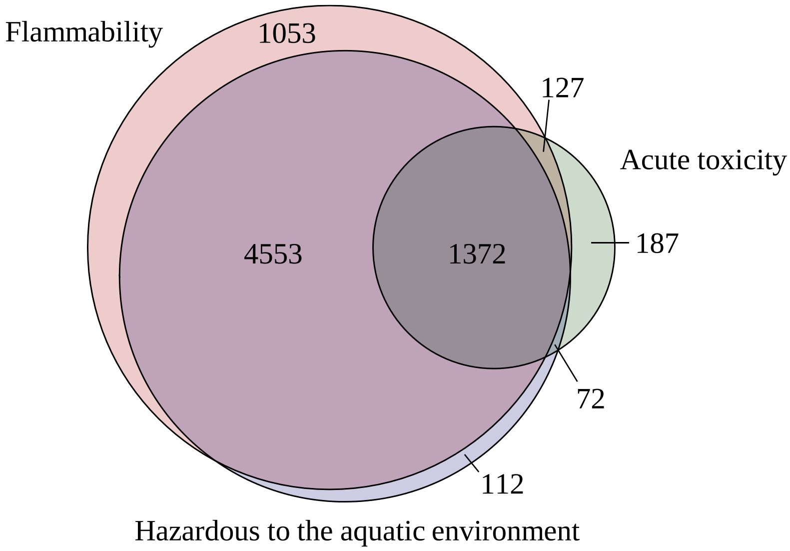


Figure 2.14. Quantitative Venn diagram reporting the distribution of the hazardous categories of the substances released in the accidents collected in the database.

A more in-depth evaluation of the features of the substances is presented in the following section, together with a detailed analysis related to the technological scenarios that occurred and the natural phenomena that caused the Natech events.

2.4 Quantified event trees for Natech events

As introduced previously, this section reports the statistical analysis of the technological scenarios that occurred with respect to the substances involved in the Natech accidents considered. The probability of technological scenarios is calculated considering the hazardous categories and the classes of the substances involved. Then, event trees are defined and quantified for each substance category, also accounting for the natural events that caused the accidents. Eventually, specific ignition probabilities are calculated for flammable liquids and gases considering three main natural events: earthquake, flood, and lightning.

2.4.1 Hazardous properties and technological scenarios

Firstly, the percentage of occurrence of each final outcome as a function of the hazardous category of the substances involved in the Natech events was calculated. The results of the analysis are reported in Table 2.7.

Table 2.7. Share among technological scenarios as a function of the hazardous properties of the substances involved in the event. See Table 2.5 for the definition of the technological scenarios.

Hazardous property	**Number of events**	**Technological scenarios**					
		F	**E**	**TGD**	**EC**	**R-NFC**	**MS**
Flammability	1053	19.5%	2%	-	-	75.8%	2.7%
Acute Toxicity	187	-	-	0%	-	100%	0%
Hazard. to aquatic env.	112	-	-	-	30.4%	69.6%	0%
Flammability + Acute Toxicity	127	11.8%	2.4%	0%	-	82.7%	3.1%
Flammability + Hazard. to aquatic env.	4553	5.8%	0.4%	-	70.6%	22.6%	0.6%
Flammability + Acute Toxicity + Hazard. to aquatic env.	1372	3.7%	0.4%	0.3%	49.8%	45%	0.8%
Acute Toxicity + Hazard. to aquatic env.	72	-	-	0%	44.4%	55.6%	0%

To obtain more specific results, an in-depth analysis was carried out considering the physical state (i.e., solid, liquid, and vapour/gas) and the chemical class (i.e., inorganic substances, organic substances) of the substance involved. As already evident from the excerpt of the substances involved, reported in Table 2.6, organic substances were involved in most of the accidents, specifically in over 60% of the entire dataset. Thus, a breakdown of the technological scenarios considering specific groups of organic substances was performed. Results are reported in Figure 2.15 for substances classified only as (*i*) flammable organic gases (red bars), (*ii*) flammable organic liquids (grey bars), and (*iii*) flammable and hazardous to the aquatic environment organic liquids (blue bars).

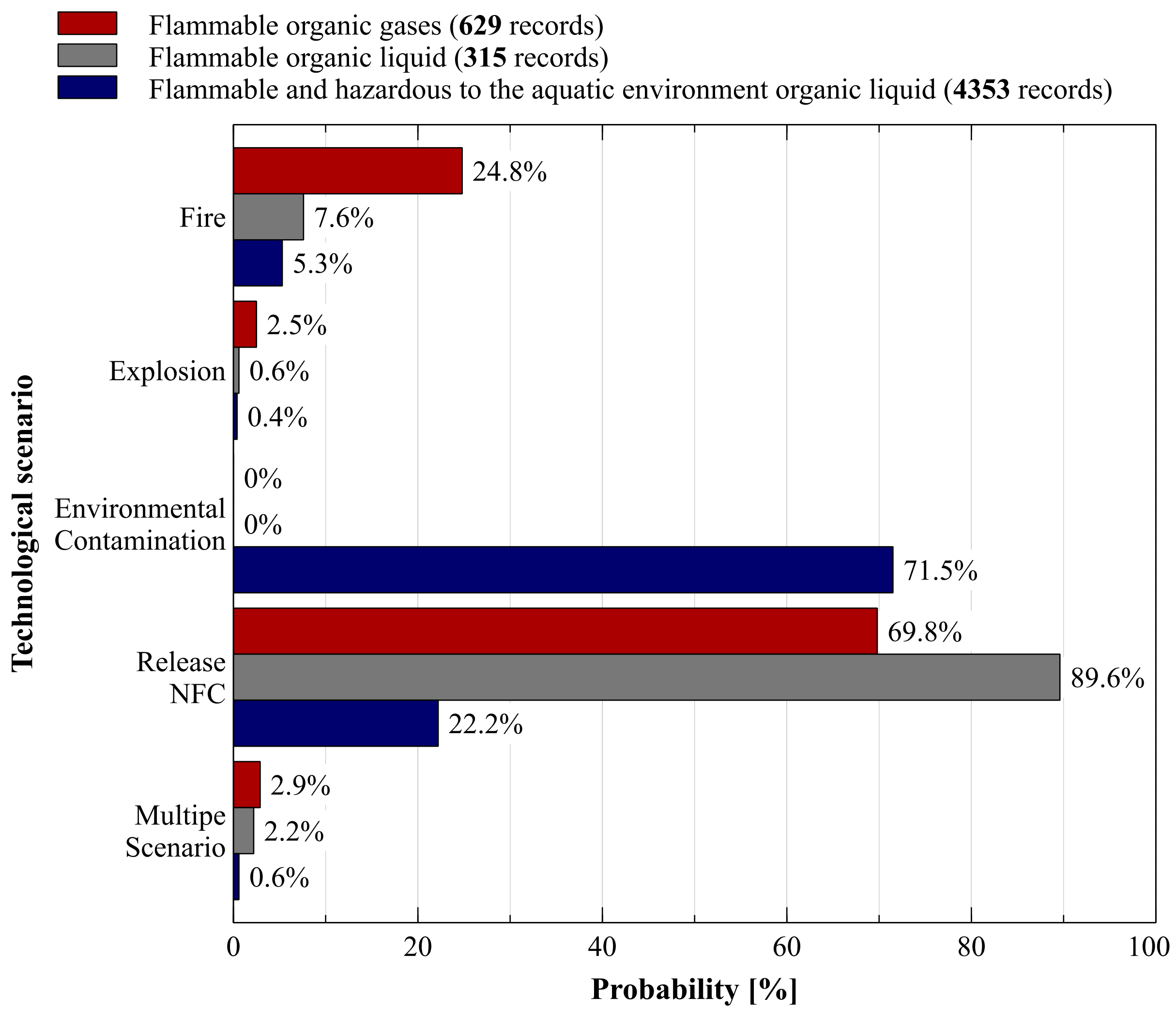


Figure 2.15. Technological scenarios occurred in the events involving the release of substances classified as flammable organic gas (red bars), flammable organic liquid (grey bars), and flammable and hazardous to the aquatic environment organic liquid (blue bars). Release NFC: Release with no further consequences.

Analysing Figure 2.15, some interesting results can be observed when comparing liquid and gaseous substances. Indeed, a probability over 27% is associated with scenarios which require an ignition source (namely "*fire*" and "*explosion*" in the present work) in the case of flammable organic gases (red bars). The same probability drops to around 8% when considering flammable organic liquids (grey bars), and an even lower value (specifically 5.7%) is obtained for liquids flammable and hazardous to the aquatic environment (blue bars). Eventually, the most frequent technological scenario associated with the last class of substances was environmental contamination, with an incidence over three times higher than the release with no further consequences.

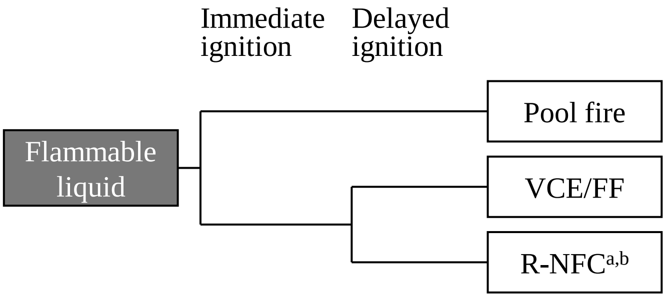
Noteworthy, the multiple scenarios that occurred in all three groups of organic substances analysed involve a technological scenario which requires an ignition source.

2.4.2 Quantified event trees

An additional analysis related to the substances released and the technological scenarios was carried out to derive event trees specific to some categories of substances and classes of natural events. The dataset used for the quantification of the event trees was a subset of that presented in the previous section (Sections 2.3.6 and 2.4.1) since events that occurred in the transportation sector were excluded from the analysis (see Table 2.5 for the definition of the sector). Thus, a total of 6408 records were considered. The analysis focused on the quantification of two event trees for substances classified as flammable (even if the substance involved may feature also other hazardous properties). The first concerns liquid substances, while the second is related to gaseous substances. Results are reported respectively in Figure 2.16 for flammable liquid substances and Figure 2.17 for flammable gas substances. In addition, the quantification was performed considering the entire dataset defined above or specific subsets based on the class of natural phenomena that triggered the event. The class of natural phenomena considered are geophysical events, hydrological events and meteorological events (see definitions in Table 2.4). Event trees were not quantified for climate-related events since the dataset available (i.e., 3 records) is not statistically relevant. Nevertheless, it is worth mentioning that a fire occurred in all records triggered by wildfire events.

The event tree related to flammable liquid substances is reported in Figure 2.16. Looking at the data, the release without ignition (i.e., the release with no further consequences, environmental contamination, toxic gas dispersion) is the most probable scenario, with a percentage higher than 90% regardless of the natural phenomena that triggered the event. In addition, the scenarios associated with a delayed ignition (i.e., vapour cloud explosions "*VCE*" and flash fires "*FF*") result to be the less frequent one, with an almost zero probability of occurrence (around 0.1%).

The results obtained for scenarios associated with immediate ignition show probabilities quite different from each other when different classes of natural phenomena are considered. Meteorological events are those for which the immediate ignition probability is higher. This result can be explained since lightning is included in the "*meteorological events*" class.

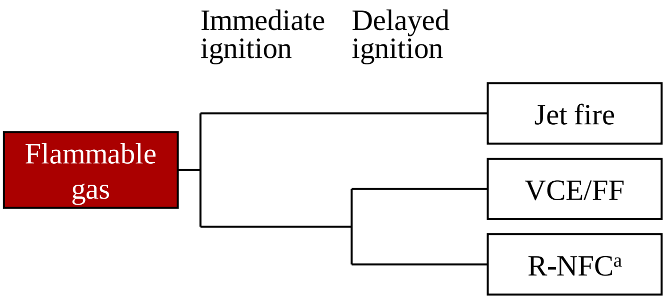


	All	Geo	Hydro	Meteo
Pool fire	6.5%	4.0%	1.3%	7.3%
VCE/FF	0.1%	NRF	NRF	0.1%
R-NFC[a,b]	93.4%	96.0%	98.7%	92.7%
Number of records	**5389**	**166**	**599**	**4616**

[a] Toxic dispersion when the substance is also toxic [b] Environmental contamination when the substance is also hazardous to the aquatic environment

Figure 2.16. Quantified event tree for flammable liquid substances. Geo: geophysical events. Hydro: hydrological events. Meteo: meteorological events. VCE: vapour cloud explosion. FF: Flash Fire. R-NFC: release with no further consequences. NRF: no records found.

Concerning flammable gases, the results are reported in Figure 2.17. Similarly to the previous case, scenarios related to release without ignition are the most probable, even if their percentage is quite lower than the case of liquid substances in most of the classes of natural events. As a consequence, the probability of scenarios where ignition occurs increases considerably. This also applies to scenarios related to delayed ignition (1.8%, around 20 times the probability calculated in the case of flammable liquid substances). Also in this case, lightning causes a higher ignition probability for the meteorological class of events.



	All	Geo	Hydro	Meteo
Jet fire	19.6%	13.4%	3.7%	21.2%
VCE/FF	1.8%	13.4%	NRF	0.7%
R-NFC[a]	78.6%	73.2%	96.3%	78.1%
Number of records	**5389**	**166**	**599**	**4616**

[a] Toxic dispersion when the substance is also toxic

Figure 2.17. Quantified event tree for flammable gaseous substances. Geo: geophysical events. Hydro: hydrological events. Meteo: meteorological events. VCE: vapour cloud explosion. FF: Flash Fire. R-NFC: release with no further consequences. NRF: no records found.

2.4.3 Probability of ignition for specific natural events

Finally, data were analysed to relate technological scenarios, substances involved and natural phenomena. The analysis aims at the calculation of ignition probability (i.e., including both immediate and delayed ignition) for specific natural events. The natural events taken into account were earthquakes, floods, and lightning. For the sake of completeness, the ignition probability regardless of the natural event was also calculated. Also in this case, a distinction between liquid and gaseous flammable substances was carried out. Table 2.8 reports the results of the analysis, together with the probability of ignition in the case of conventional accidents available in the literature [5].

The ignition probabilities calculated in the present study are comparable to those available in the literature for conventional accidents, especially when considering the value calculated regardless of the natural event (labelled as "*All*" in Table 2.8). In dealing with specific natural events, some peculiarities can be observed. Indeed, lightning results in a quite high ignition probability, greater than those for other natural events and conventional accidents both for liquid and gaseous substances. This also confirms the trend obtained in the quantified event trees reported in Figure 2.16 and Figure 2.17. Flood events, instead, report lower ignition probabilities, below the values considered for conventional accidents and overall Natech events. Eventually, the ignition probability derived for earthquakes is comparable to those considered for conventional accidents.

Table 2.8. Probabilities of ignition for specific natural events. Values in the case of conventional scenarios are also reported [5].

Natural events	Probability of ignition	
	Flammable gas	**Flammable liquid**
All	21.4%	6.6%
Lightning	52.8%	49.8%
Earthquake	32.1%	5.8%
Flood	4.1%	1.3%
Conventional scenarios	20-70%	6.5%

2.5 Focus on extreme temperatures

One of the most evident effects of climate change is the variation of mean temperature [57], as introduced in Section 1.2. Indeed, climate change can lead to a change in the mean temperature, shape and variance of temperature distributions. These variations, individually or combined, can lead to changes in frequency, intensity, duration and spatial extent of extreme weather events, among which also extremely low temperatures (cold wave) and extremely high temperatures (heat wave) [58]. Despite the relevance of the issue, limited attention was devoted to the study of the interactions between extreme temperature conditions and industrial installations, as illustrated in Section 1.3. For this reason, a focus on extreme temperature is performed to provide indications based on past events for the development of methodologies for quantifying the risk due to extreme temperature conditions.

The trend over the year of Natech events associated with cold waves and heat waves is reported in Figure 2.18 (panels a and b respectively). The figure shows an increasing number of events in recent years. Moreover, the figure reports also the number of natural events related to cold waves and heat waves according to the data provided by the EM-DAT database [1]. Comparing the data, it can be observed that the trend of Natech accidents somehow reflects that of natural events.

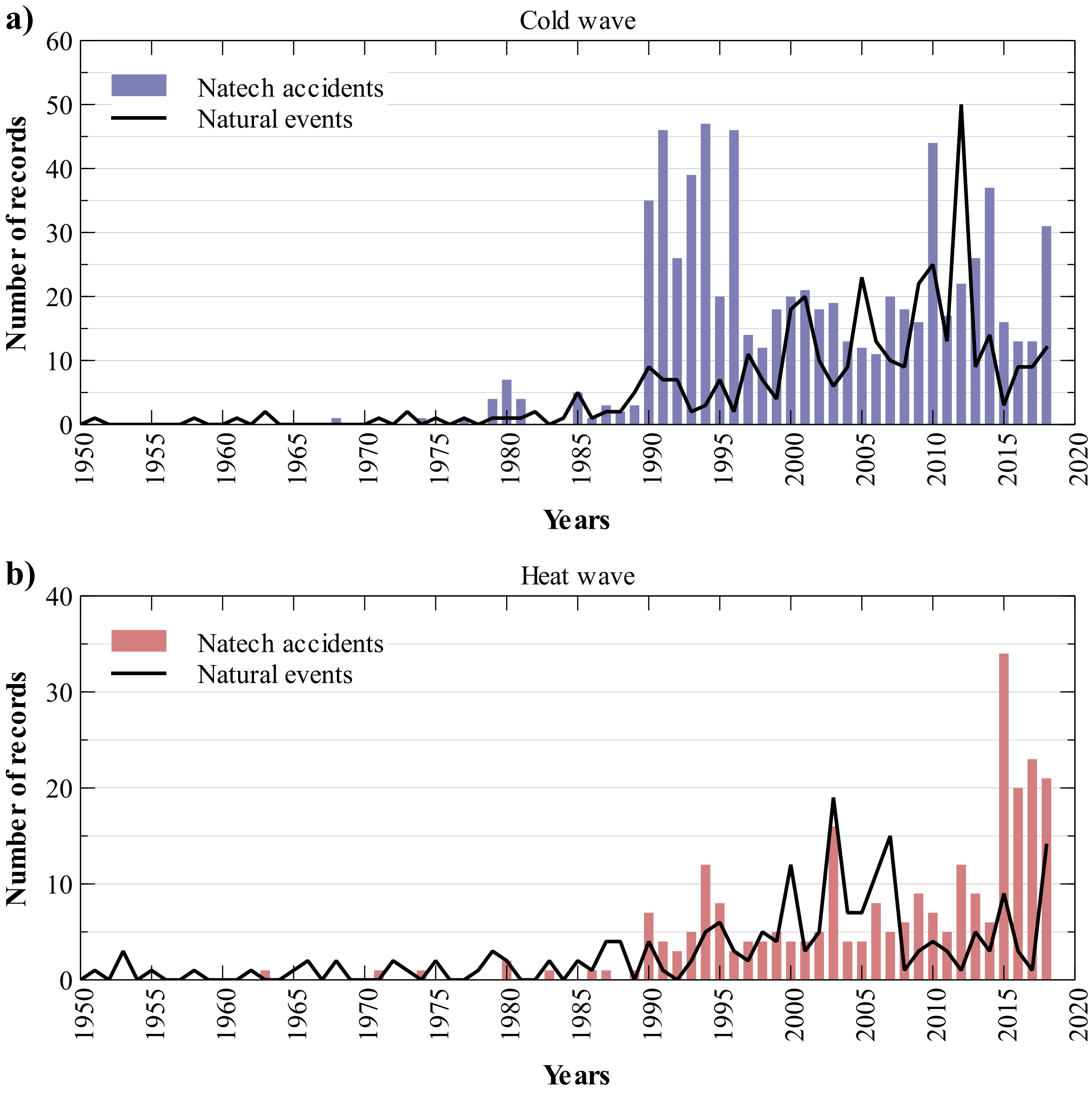


Figure 2.18. Time trend of the records collected for (a) cold waves and (b) hot waves compared to the trend of natural events for the same categories (black lines).

Detailed analyses related to cold wave and heat wave-induced accidents are carried out in the following sections (Sections 2.5.1 and 2.5.2). Results on the technological scenarios that took place in the accidents, the substances involved, and the equipment items affected by the natural event are obtained. Eventually, a specific study on the primary events that occurred in the accidents is carried out.

2.5.1 Cold wave-induced accidents

Around 73% of the records collected in the database related to extreme temperatures are caused by cold waves. Figure 2.19 shows the share among the technological scenarios (see definitions in Table 2.5) that occurred in Natech accidents caused by cold waves. The environmental contamination represents the most probable final outcome, followed by the release with no further consequences (Release NFC), which together represent over 85% of the entire dataset. The overall percentage of these two scenarios is similar to the one obtained considering the entire database (see Figure 2.11) even if more accidents resulted in environmental contamination. Eventually, the other final scenarios (e.g., fire, explosion) occurred a limited number of accidents.

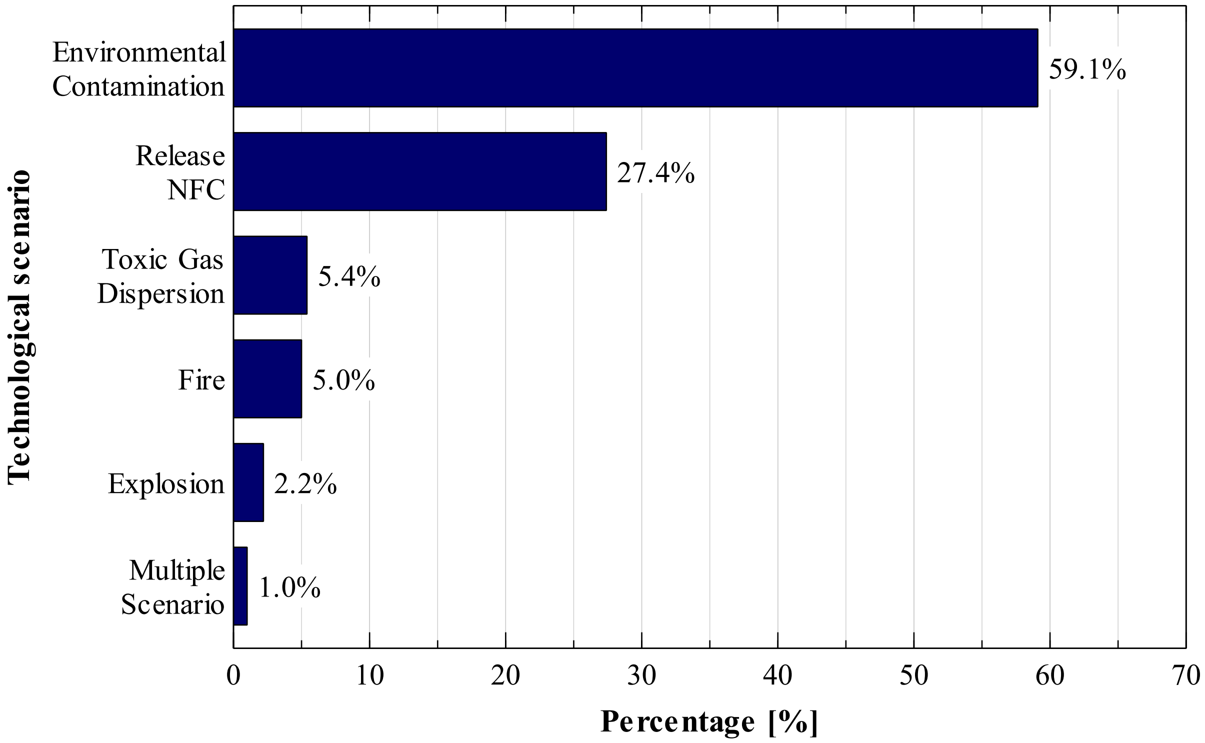


Figure 2.19. Share among the technological scenarios that occurred in the cold wave accidents included in the database. Release NFC: Release with no further consequences.

Figure 2.20 shows the share among the substances released in accidents caused by cold waves. Organic substances still represent the majority of substances involved, as for the case of the entire dataset reported in Table 2.6. Indeed, fuel oils are involved in just under 20% of cases. Other oils, such as crude oil and those referred to as “oil (not better specified)”, are released in around 12% of accidents.

Eventually, it is worth mentioning that most of the substances labelled as "*other substances*" in Figure 2.20 are organic substances (e.g., lubricating oil, hydraulic oil, motor oil).

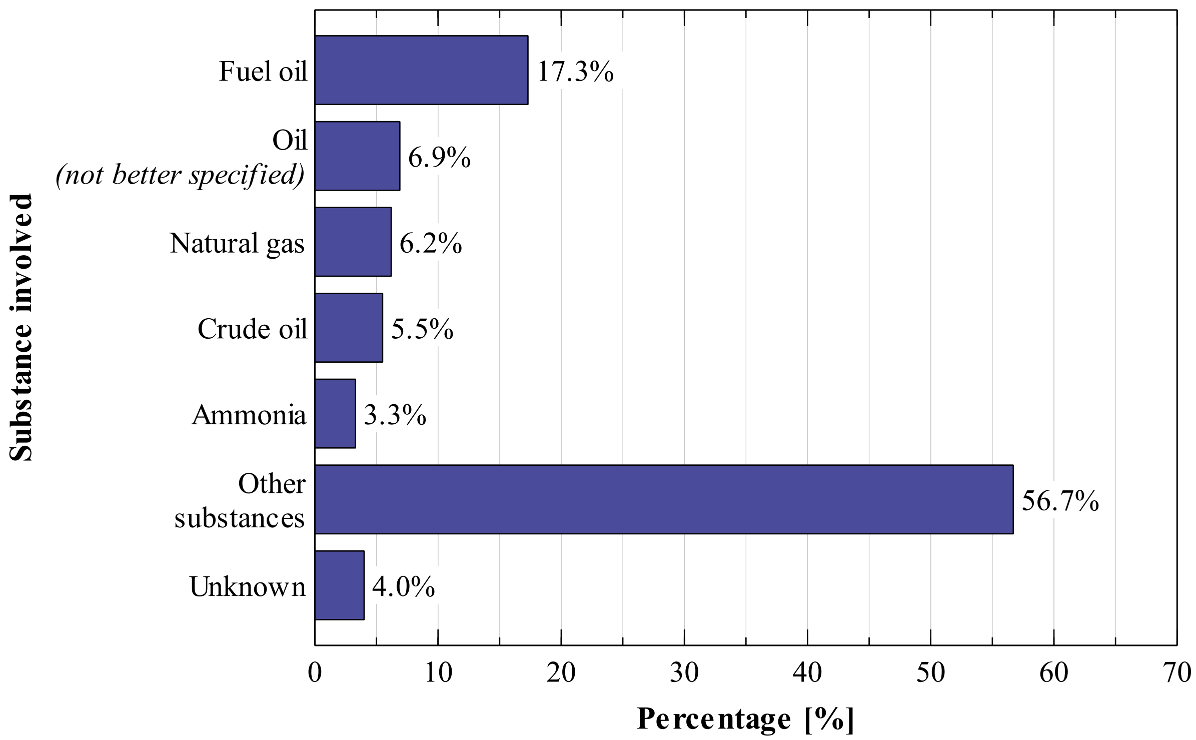


Figure 2.20. Substances that are involved in accidents caused by cold waves.

Then, the equipment items involved in the cold wave-related Natech events are considered. The items identified are merged into categories, which are defined by adapting the classification provided by Iaiani et al. [59] and Tugnoli et al. [60]. The identified categories and related examples are reported in Table 2.9. It is worth mentioning that the information on the equipment item involved in the accident is not available for all the records (see Sections 2.3.5 and 2.3.6).

Figure 2.21 reports the breakdown of equipment categories that are involved in accidents caused by cold waves. Pipelines are the items most affected, being involved in over one-third of the accidents that occurred. Transportation equipment, storage equipment, valves and instrumentations are also frequently affected by cold waves, with an incidence of about 13% each. Information on the equipment involved in the accident is not reported for around 10% of the cases, whereas in 4% of the accidents the equipment involved is not related to the categories defined in Table 2.9. Eventually, warehouses and landfills seem to be not affected by cold-wave according to the collected data.

Table 2.9. Categories of the equipment items that are mainly involved in Natech events caused by extreme temperatures. General categories for the classification of plant items are adapted from Iaiani and co-workers [59] *and Tugnoli and co-workers* [60].

Equipment category	**Examples**
Storage equipment	Atmospheric storage vessel, pressurized storage vessel, …
Process equipment	Column, reactor, heat exchanger, …
Valves and instrumentation	Valves, control devices, …
Pumping equipment	Pump, compressor, ...
Warehouse	Packed material, spare material, …
Pipeline	Pipelines, pipeworks, …
Transportation equipment	Road tanker, rail tanker, tanker, …
Landfill	Landfill

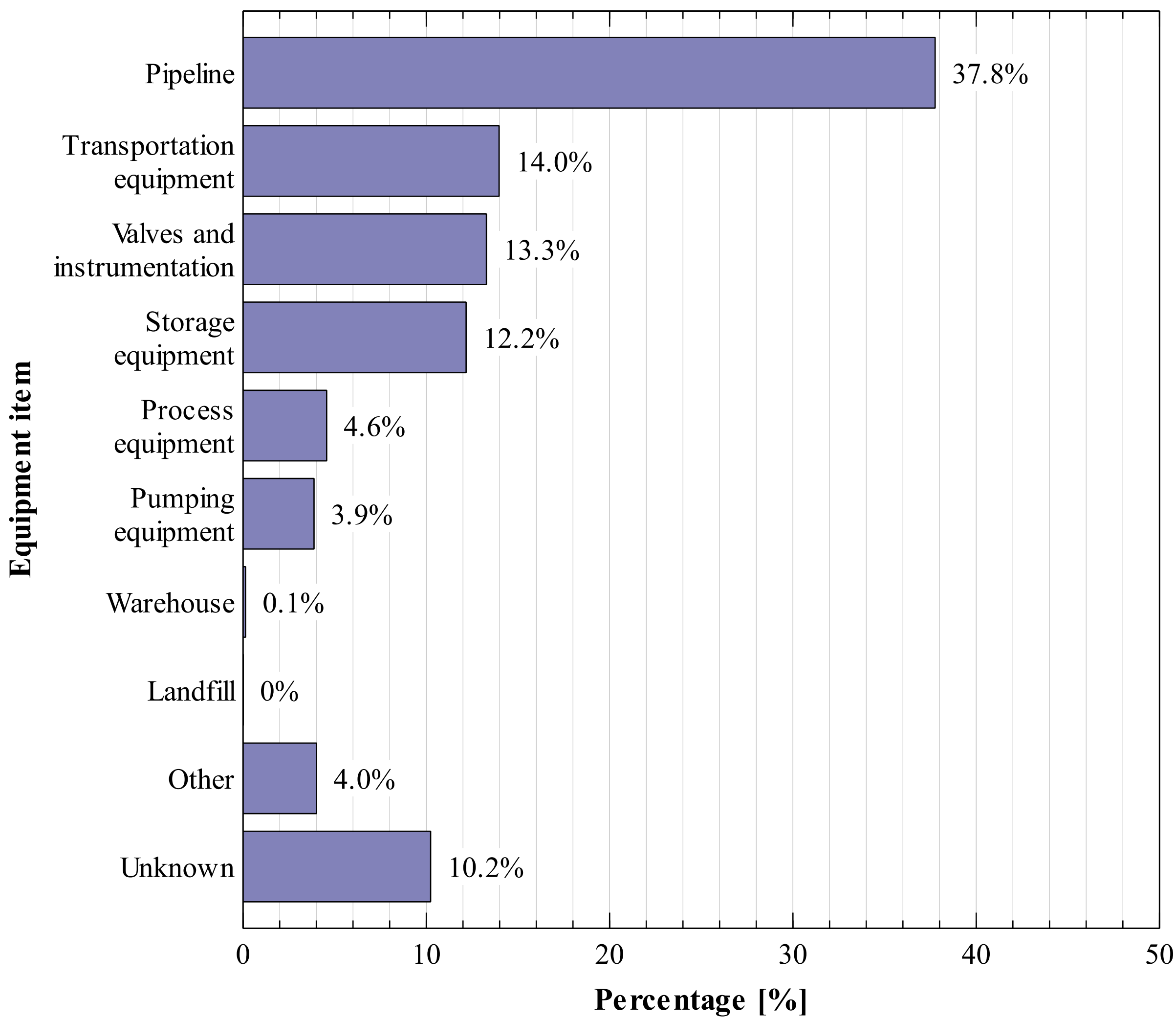


Figure 2.21. Equipment items involved in cold waves-related Natech events.

These results are paramount to guide the development of new methodologies for quantitative risk assessment, pointing out which equipment should be given more attention. From this perspective, it is very important to identify primary events that occurred in the accidents, that somehow reflect the failure mode of equipment items. Indeed, primary events represent the direct consequence of the cold wave on installations, which in turn causes the accident. As in the previous case, information on primary events are not available in all records. Thus, only accidents which involve equipment typically used in the chemical and petrochemical sector are considered (see Table 2.3 for the definition of the industrial sectors). Specifically, storage equipment, process equipment, valves and instrumentation, pumping equipment and pipeline are analysed (see Table 2.9 for the definition of the categories).

Five main primary events were identified in the case of cold wave-related Natech accidents: *(i)* power outage, *(ii)* brittle fracture, *(iii)* ice formation, *(iv)* process fluid solidification, and *(v)* external load due to ice or snow. Figure 2.22 report the percentage of occurrence of each primary event together with a breakdown of the related equipment items for cold waves.

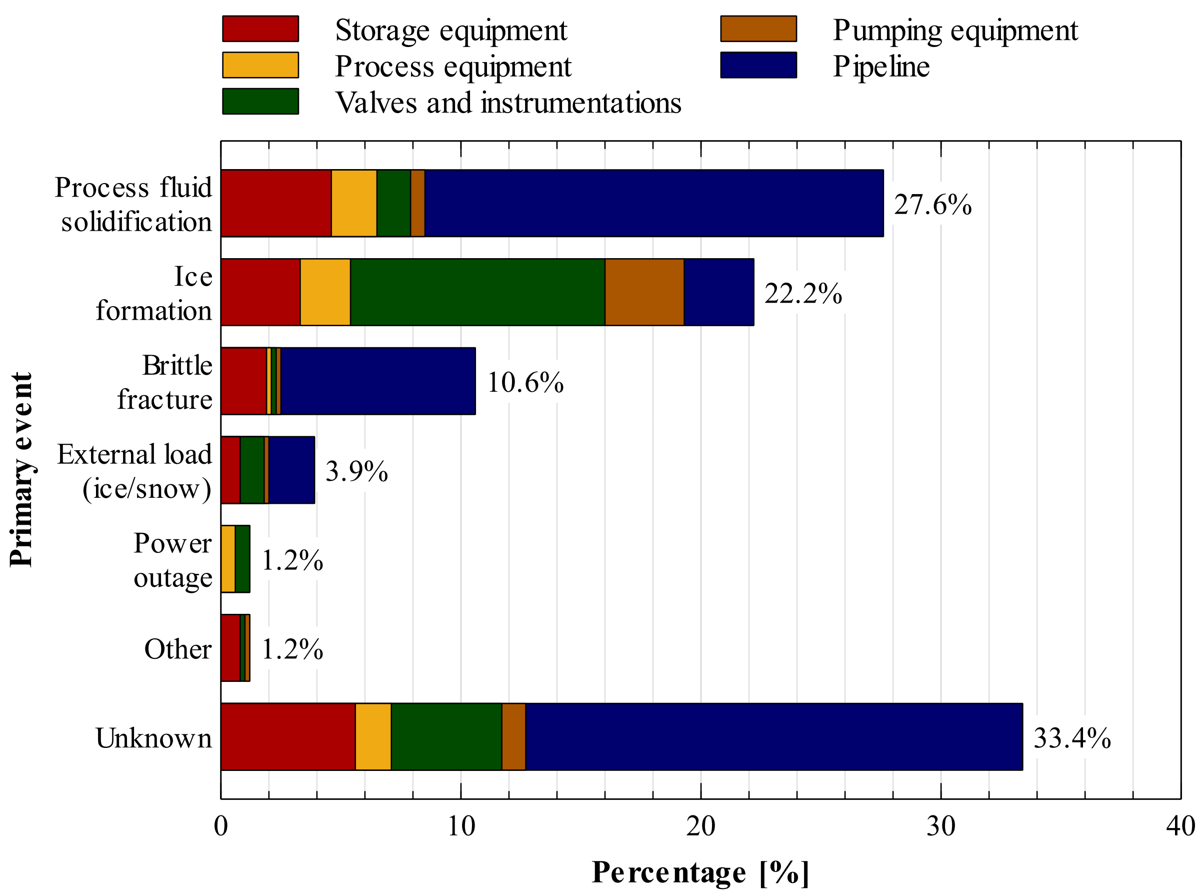


Figure 2.22. Share among primary events and relation with the category of equipment items involved in the accident in the case of cold waves.

Most of the accidents are related to the solidification of the process fluid (27.6% of the records). In such cases, the process fluid inside the equipment (process water or other substances) solidifies forming plugs or blocks within the item. These in turn can stop the flow or are free to move inside the equipment. The solidification of the process fluid mainly occurs in pipeworks. Specifically, pipeworks subjected to a discontinuous flow, such as bypass pipes, are those most frequently involved in these accidents, since this condition makes the phase transition easier. Different behaviour is associated with ice formation, which occurred in 22.1% of the records associated with cold waves. Indeed, this case refers to the solidification of water from the external environment. This condition is particularly critical in the case of valves and instruments, as the formation of ice on the equipment can prevent its correct operation, leading to the release of hazardous substances. Another important failure mode in the case of cold waves is represented by the brittle fracture of equipment items (11.2% of the cases). Indeed, the lowering of the temperature leads to a reduction of the mechanical resistance of the materials which may incur in brittle fracture. Other primary events are related to the rupture of equipment due to an undesired external load such as snow or ice (4%), power outage (1.1%), and other events such as vacuum collapse induced by vapour condensation.

2.5.2 Heat wave-induced accidents

Around 73% of the records collected in the database related to extreme temperatures are caused by heat waves, and Figure 2.23 reports the technological scenarios that occurred in accidents caused by such events.

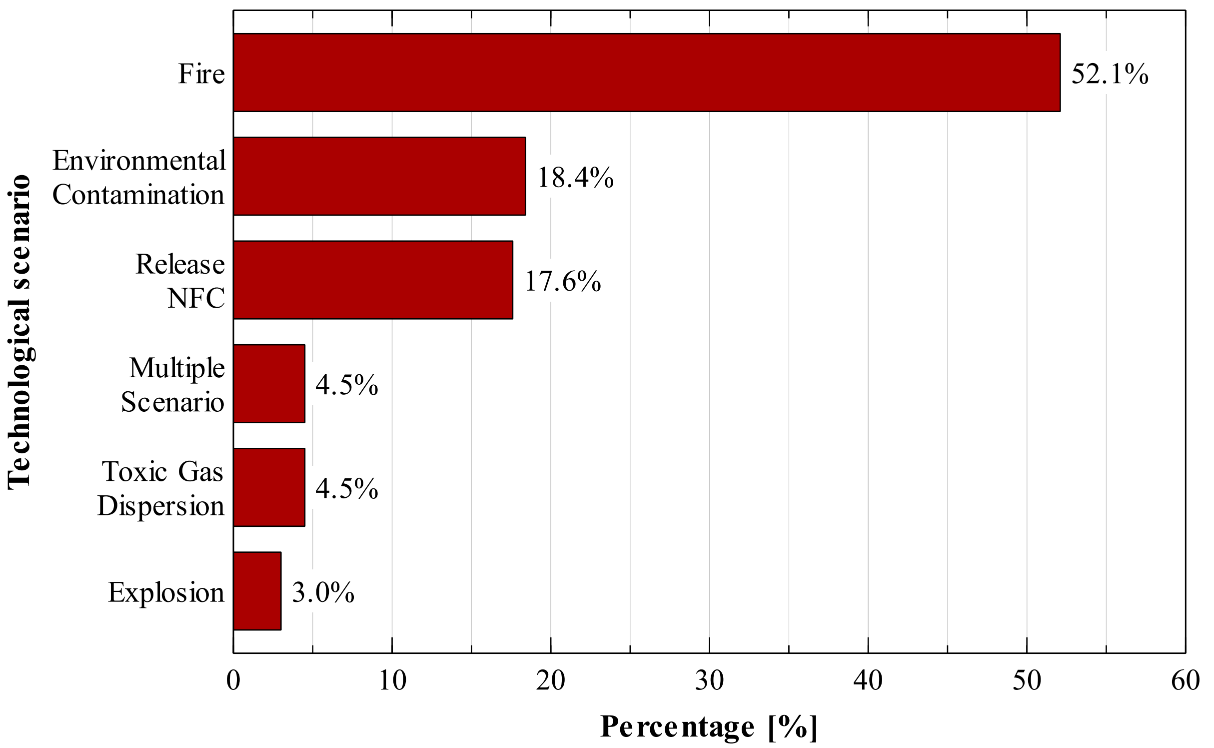


Figure 2.23. Share among the technological scenarios that occurred in the heat wave accidents included in the database. Release NFC: Release with no further consequences.

A significant difference can be observed between these results and the share among the technological scenarios that was obtained considering the entire database (see Figure 2.11). Indeed, accidents led to a fire in over 50% of the cases considering heat wave-related events, while the percentage was less than the 10% accounting for the entire dataset. This suggests that the heat waves, besides triggering the accident, can somehow provide the ignition source. Consequently, the percentage related to other final outcomes such as environmental contamination or release without further consequences is reduced, and it is around 18% for each of the two scenarios.

As for the case of cold waves, the equipment items affected by heat waves are analysed. The categories of equipment accounted for are the same used previously, and they are reported in Table 2.9. Storage tanks are the most vulnerable equipment in case of heat waves, and these are involved in about 18% of the cases. Moreover, heat waves also pose a problem for the waste treatment sectors as several accidents have occurred in landfills (12.7% of heat wave-related accidents). Eventually, it is worth mentioning that records related to heat waves are generally characterized by a lower level of detail, which does not allow for the identification of relevant aspects of the accidents. Indeed, the equipment items involved in the events were not reported in more than 30% of the records.

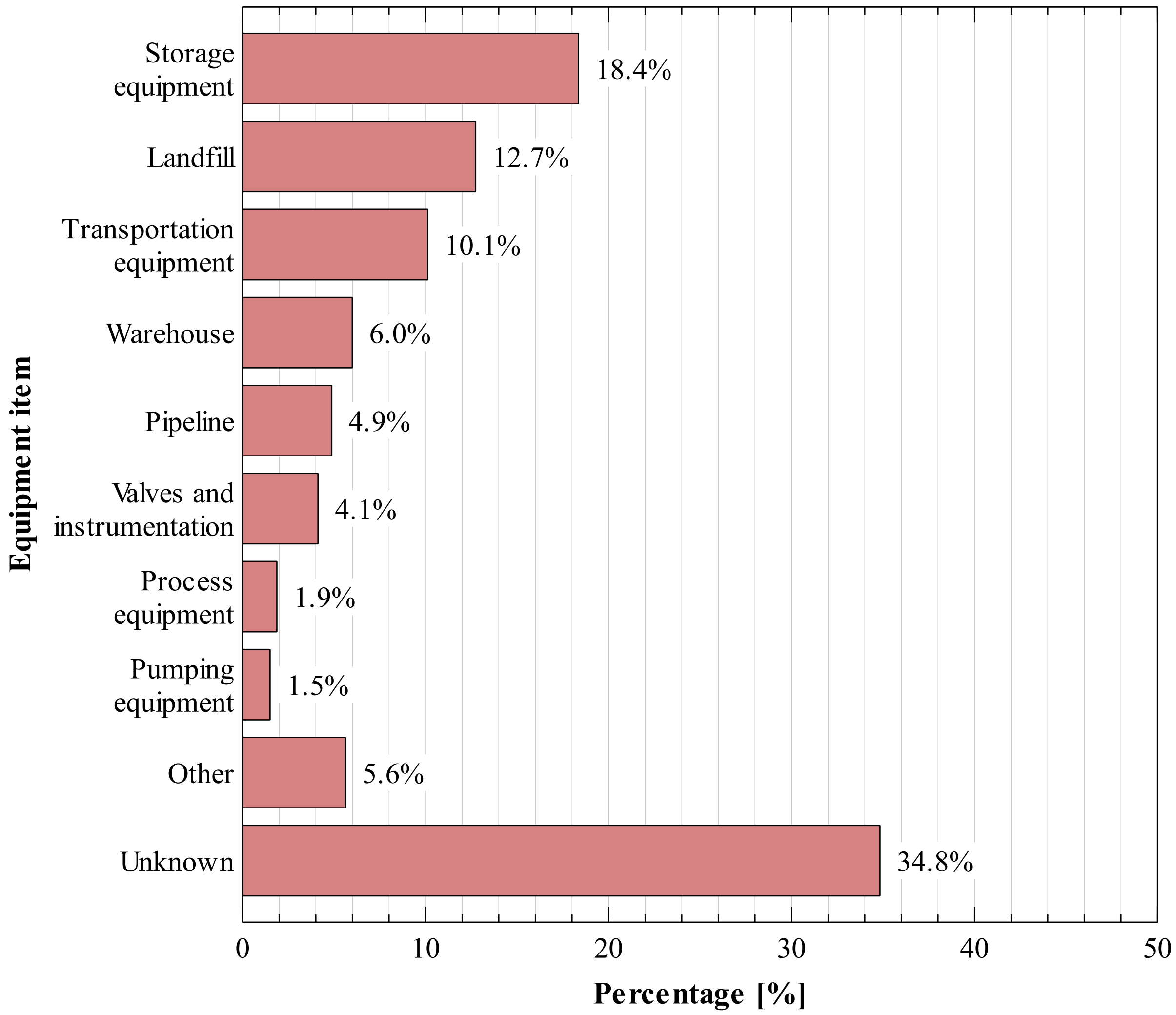


Figure 2.24. Equipment items involved in heat waves-related Natech events.

Then, the substances involved in heat wave-related accidents are identified, and the results are reported in Figure 2.25. These are quite different compared to cold wave-related accidents and the data referring to the entire database. Indeed, the substances most involved are wastes. Despite this, the result is not surprising in light of the equipment items affected. Hence, wastes result in a relevant substance in the case of heat waves since several accidents occurred in landfills. The other substances involved are in line with the results obtained previously. The lower level of detail of such records is reflected also here, as the substance involved in the accident was not reported in over 30% of cases.

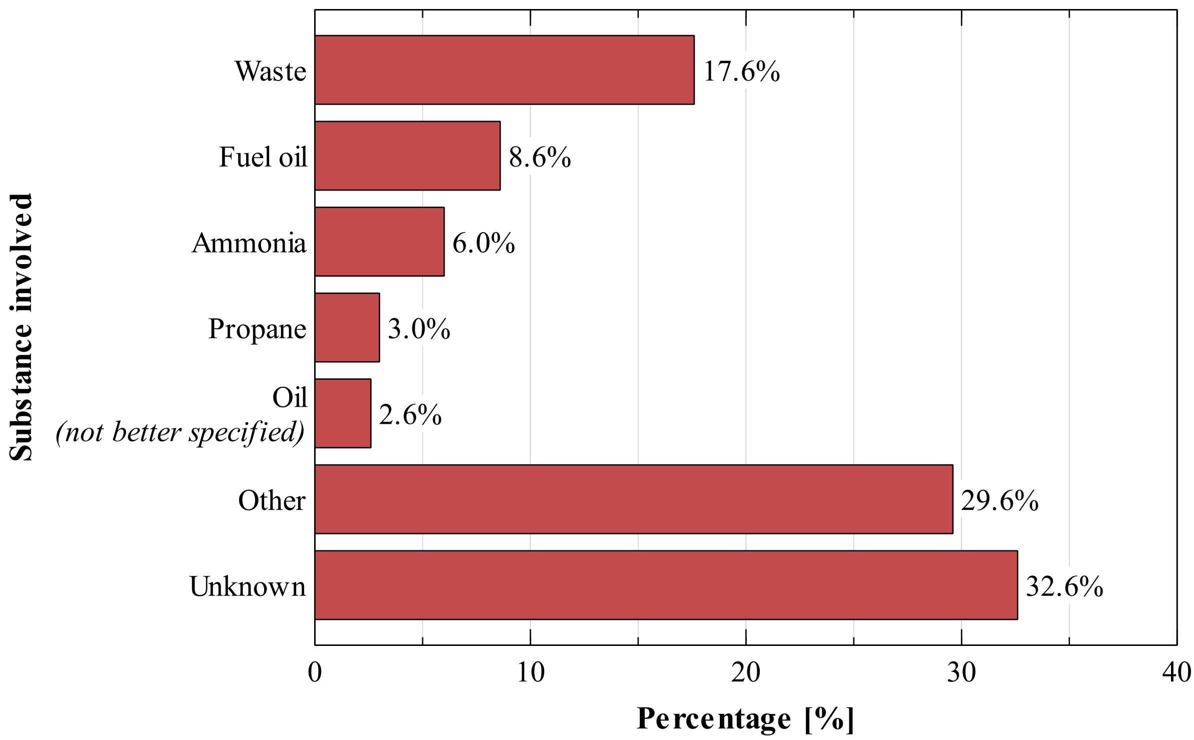


Figure 2.25. Equipment items involved in heat waves-related Natech events.

Eventually, the primary events that occurred in heat wave-related accidents are evaluated. Only two primary events are identified in the case of heat waves, and these are *(i)* pressure increase and *(ii)* power outage. Figure 2.26 report the percentage of occurrence of each primary event together with a breakdown of the equipment items involved in the case of heat waves. Noteworthy, the same equipment categories considered for the case of cold waves are accounted for, specifically storage equipment, process equipment, pumping equipment, pipeline, and valve and instrumentation. The increase in the pressure of the equipment items occurred the 65.6% of the cases, while a power outage took place in only 1.2% of the accidents. Similarly to the previous analysis, the percentage of records in which the information is not provided is around 30%.

The pressure increase is generated by an expansion of the process fluid inside an equipment item caused by the high temperature. This may cause an equipment failure or the release of fluid through venting systems, such as pressure safety valves. The most exposed items to such events are storage tanks, which contain a high quantity of hazardous materials. Moreover, these equipment items are more subject to undergo a pressure increase under the effect of heat waves since the substances can remain inside storage equipment for a long time. As for the power outage, the heat waves caused malfunctions of the power distribution systems or related equipment items (e.g., transformers). The interruption of the power supply to a section or the entire plant compromises the normal operability of the site causing the accident.

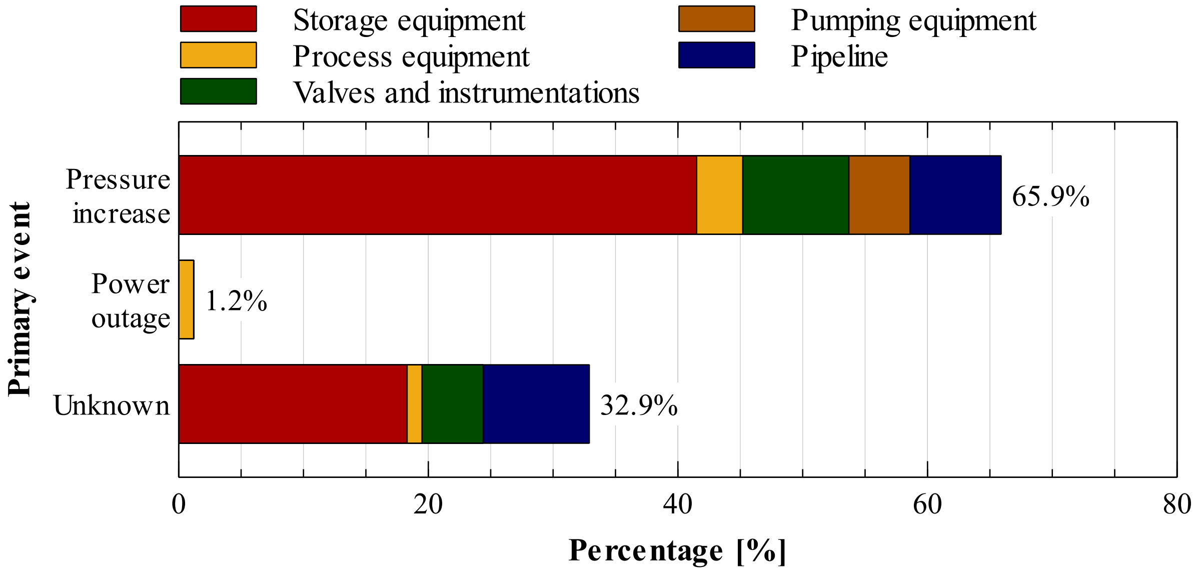


Figure 2.26. Share among primary events and relation with the category of equipment items involved in the accident in the case of hot waves.

2.6 Focus on wildfires

As mentioned in Section 2.3.3, three wildfire events triggering Natech accidents were recorded in the database. Despite the low incidence in the database, the increasing risk related to wildfire suggests performing a further analysis of these events, which may be interpreted as early warnings. Section 1.2 reports that global warming is lengthening hot and dry seasons, thus influencing fire regimes and promoting the conditions for the ignition of wildfires [61–66]. Furthermore, the occurrence of severe wildfires in the last years (such as in Portugal, Greece, and California) increased the concern related to such events. Thus, the study of the possible interaction between wildfire and industrial installations is paramount to avoid technological scenarios triggered by such events, as also addressed by Kern and Krausmann [67].

Given the small number of accidents collected, a statistical analysis is not relevant. However, studying the accident dynamics that occurred is useful to understand the possible pathways through which a wildfire can affect an industrial site.

Table 2.10. Details on the three accidental records triggered by wildfires collected in the database.

Field	Description
	Accident #1
Source	NRC #1175089
Date	05/04/2017
Where	Wynona, Oklahoma, USA
Technological scenario	Fire
Equipment item	Pipeline
Substance involved	Crude oil
Damage to humans	Not available
Economic losses	Not available
Summary	An exposed pipe was damaged by a grassfire resulting in a spill of crude oil that ignited
	Accident #2
Source	NRC, #1219914
Date	28/07/2018
Where	Redding, California, USA
Technological scenario	Fire
Equipment item	Pipeline
Substance involved	Natural gas
Damage to humans	Not available
Economic losses	> 50000 $
Summary	An unknown amount of natural gas has been released due to the wildfires and ignited. Accessible gas lines are in the process of being shut-down. Estimated damages are greater than 50000 dollars.
	Accident #3
Source	ARIA, #23132
Date	25/12/1997
Where	Bintulu, Malaysia
Technological scenario	Explosion
Equipment item	Air separation unit
Substance involved	Aluminium/Oxygen
Damage to humans	12 slight injuries
Economic losses	Not available
Summary	At 10:50 pm., an explosion occurred in the distillation column of an air separation unit (ASU) that provides oxygen to the petrochemical industry. The explosion caused 12 slight injuries and damage up to 5

Field	Description
	km. The unit was destroyed, and surrounding units were heavily damaged. The ASU plant capacity was 2500 t/d of oxygen at 99.8% purity; it was put in service in 1991. The lower section of the low-pressure column consisted of aluminium structured packing fitted in an internal shell. The accident resulted from the pollution of the LOX closed-loop due to particulate material in the air (intense forest fires at that time) and organic pollutants from the washing process. The hydrocarbon pollutant acted as an igniter and the fuel was aluminium in liquid oxygen.
Other information	An investigation of the accident was conducted by van Hardeveld and co-workers in 2001 [68]. The results confirmed that the root cause of the explosion was the forest fire nearby the plant. Additional information can be found in the original paper.

The analysis of the chain of events that occurred in the three accidents allows identifying two main pathways: direct damages and indirect damages. These considerations are in line with the work of Kern and Krausmann [67] which suggests considering the direct and the indirect effects of the wildfire, and relates the latter with events linked to supply chains, business activities, emergency measures or other types of plant-related activities. As for the direct damages, *Accidents #1 and #2* are caused by the wildfire flames, even if it is not clear if a flame impingement occurred or if the accidents were caused by the thermal radiation from the wildfire. Despite this, both these pathways seem to be reasonable in the case of wildfire. Eventually, the last accident collected (*Accident #3*) was caused by a wildfire which was not at the plant boundary, and the effects of the wildfire are mainly related to the presence of smoke and firebrands in the atmosphere. Figure 2.27 reports a summary of the possible wildfire hazards for industrial installations. In addition, Figure 2.28 schematizes the three main types of direct hazards recognized by the accident records collected: *(a)* flame impingement, *(b)* thermal radiation, and *(c)* firebrands.

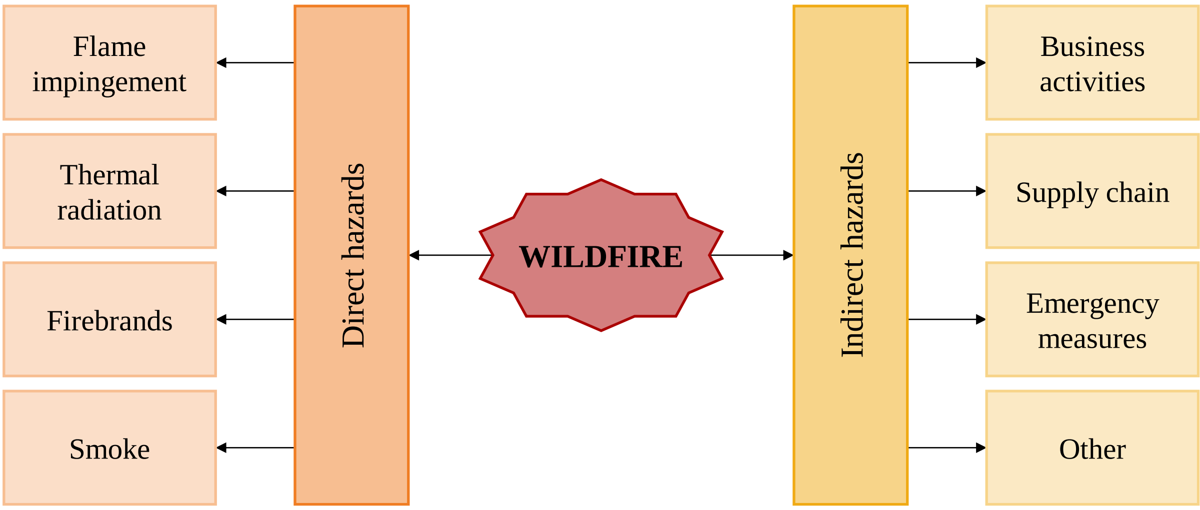


Figure 2.27. Direct and indirect pathways through which wildfire can affect industrial installations based on the records collected in the database.

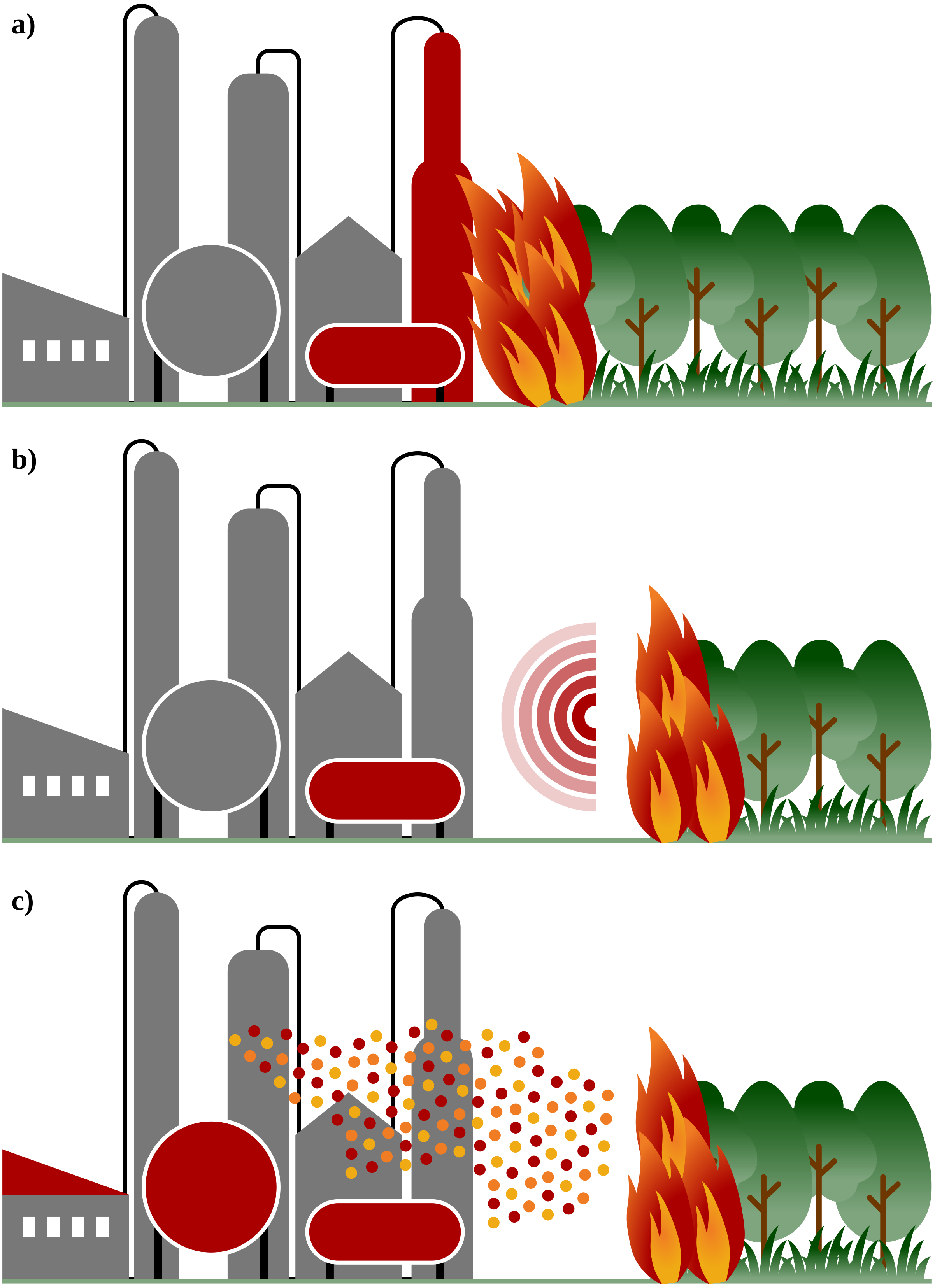


Figure 2.28. Type of direct hazards from wildfires to industrial installation: (a) flame impingement, (b) thermal radiation, and (c) firebrands. Figure adapted from Kern and Krausmann [67].

Another important result can be derived from the analysis of the records. Indeed, all the accidents lead to a final outcome which requires an ignition source. Thus, wildfires, besides causing the loss of containment of hazardous substances, probably represent also the source of ignition.

2.7 Conclusions

The present chapter aimed at providing a comprehensive analysis of Natech accidents that occurred in the chemical and process industries. This was performed through a historical analysis. An extended database of Natech accidents containing 9100 records was built and analysed. Overall, an increasing trend over time of Natech events is observed, even if there are difficulties in collecting homogeneous data worldwide. Meteorological events resulted to be the main trigger of Natech scenarios, being storms and tropical storms the causes of the majority of the collected accidents. Natech events triggered by earthquakes resulted to be the most catastrophic in terms of damages to humans and assets.

Quantified event trees were obtained for specific categories of substances which may support a more effective assessment of technological scenarios triggered by natural events. Moreover, probabilities of ignition in case of release were obtained for Natech events triggered by earthquakes, floods, and lightning.

The database also allowed a preliminary investigation of Natech events caused by extreme temperatures and wildfire-induced accidents. The results allow the identification of possible routes through which extreme temperatures and wildfires may affect industrial installation, addressing future research on Natech accidents triggered by these specific natural events.

Overall, the results obtained in the present chapter remark the importance of Natech accidents in the framework of the quantitative risk assessment. The results also represent a step toward the identification and assessment of the specific features of Natech events in the chemical and process industry.

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Chapter 3: SAFETY DISTANCES TO PREVENT NATECH ACCIDENTS DUE TO WILDFIRE EVENTS IN THE WILDLAND-INDUSTRIAL INTERFACE

Climate change and global warming are making weather conditions around the world increasingly favourable to the development and spread of wildfires. A large number of extreme wildfires occurred in recent years, and they become a potential threat to humans when approaching the Wildland-Urban Interface (WUI) or the Wildland-Industrial Interface (WII). The Wildland-Industrial Interface is characterised by the presence of a large inventory of hazardous compounds and the fire exposure may lead to severe Natech events and even trigger domino effects, worsening the consequences of the wildfire alone. To ensure the integrity of equipment items, a methodology for the evaluation of safety distances between storage tanks and vegetation is presented. The methodology is based on the characterization of the wildfire scenario according to the type of vegetation involved and on the application of simplified models to assess the vulnerability of tanks.

3.1 Introduction

Wildfires are uncontrolled fires involving the combustion of wild vegetation. As introduced in Section 1.2, global warming is enhancing the development of wildfires, promoting favourable conditions for ignition and rapid spread. When this type of event approaches anthropic settlements at the so-called Wildland-Human Interface, it becomes a potential threat to humans, civil structures and industrial facilities [1], posing complex management challenges in terms of civil protection and fire mitigation [2]. Johnston and Flannigan identified three interfaces between wildland and human-built areas:

- Wildland-Urban Interface (WUI): an area where homes, public buildings and commercial structures meet with or are dispersed within wildland vegetation.
- Wildland-Infrastructure Interface: an area where infrastructures (e.g. roads, railways, or powerlines) meet with or are dispersed within wildland vegetation.
- Wildland-Industrial Interface (WII): an area where industrial facilities (e.g. chemical plants, oil depots, warehouses) meet with or are dispersed within wild vegetation.

Besides global warming and the development of extreme fires in the last years (see Section 1.2), the concern about wildfires reaching anthropic developments is growing due to the fast urbanization and the rapid industrial development in rural areas, thus increasing the extension of the WUIs and WIIs [3,4]. This has promoted the investigation of safety-related aspects of the interaction of wildfires with human structures. In the last decade, many researchers focused on the WUI [5–9], as already discussed in Section 1.3, while the WII has only recently started to attract attention. Especially in chemical industries or oil refineries, where a large inventory of hazardous substances is present, fire exposure (such as the exposure to a wildfire event) may lead to catastrophic events [10–13] and even trigger domino effects [14], worsening the consequences of the wildfire alone. From this perspective, the present section aims at answering the following research question:

In the case of wildfires impacting industrial sites, how to ensure the safety of the plant?

In Chapter 2, several possible pathways through which a wildfire can impact industrial installations were identified. Focusing on direct pathways (i.e., fire impingement, thermal radiation, firebrands, and smoke), storage tanks are among the most vulnerable pieces of equipment since they are usually located in the proximity of the plant boundary. Indeed, experimental and numerical studies demonstrated that storage tanks can be seriously affected by wildfire exposure [8,15]. Furthermore, storage tank integrity is paramount considering the large amounts of hazardous materials that they may contain.

The provision of adequate safety distances between storage tanks and vegetation may avoid tank failure and the spread of wildfire inside the plant. In industrial practice and regulations, separation distances are currently defined through rules-of-thumb based on empirical values [16], without performing an assessment that considers the fire radiation and the resistance of the target. Thus, no systematic and quantitative approaches are available to establish appropriate safety distances based on sound technical criteria.

The present study aims at filling this gap, proposing a methodology for the evaluation of safety distances between storage tanks and vegetation that may be affected by a wildfire (Section 3.2). The methodology is based on the characterization of the wildfire scenario and on the application of vulnerability models to assess the integrity of specific categories of tanks. Three case studies are defined in Section 3.3 to demonstrate the applicability of the methodology. Safety distances resulting from the application of the methodology are presented in Section 3.4, and a comparison with existing separation distances prescribed by regulations and guidelines is reported in Section 3.5. The strengths and limitations of the proposed approach are discussed in the same section. Eventually, conclusions are drawn in Section 3.6.

3.2 Methodology for safety distances definition

As introduced in the previous section, the provision of adequate safety distances between wild vegetation and industrial installations is paramount to avoid the spread of wildfires to equipment items. Thus, a methodology for the calculation of safety distances was developed.

The present section aims at presenting the procedure for the calculation of the separation distances. The flowchart of the methodology is reported in Figure 3.1. The methodology consists of 4 main steps:

- Step 1: Characterization of the wildfire scenario, namely the definition of the flame shape, dimensions, and fire emissive power.

- Step 2: Evaluation of the thermal radiation on targets. This step can be developed in the absence of protections on the tanks or considering the implementation of safety barriers.
- Step 3: Calculation of the time to failure of targets. Generic assessment of the time to failure can be performed considering only the type of target (i.e., atmospheric tanks, pressurized tanks), while a specific assessment can be carried out also considering its volume.
- Step 4: Definition of safety distances. This step performs the calculation of the safety distances. Generic safety distances are defined when the generic assessment is carried out in step 3, while specific values are obtained implementing the specific assessment of the time to failure defined in Step 3.

Each step of the methodology is described in detail in the following sections.

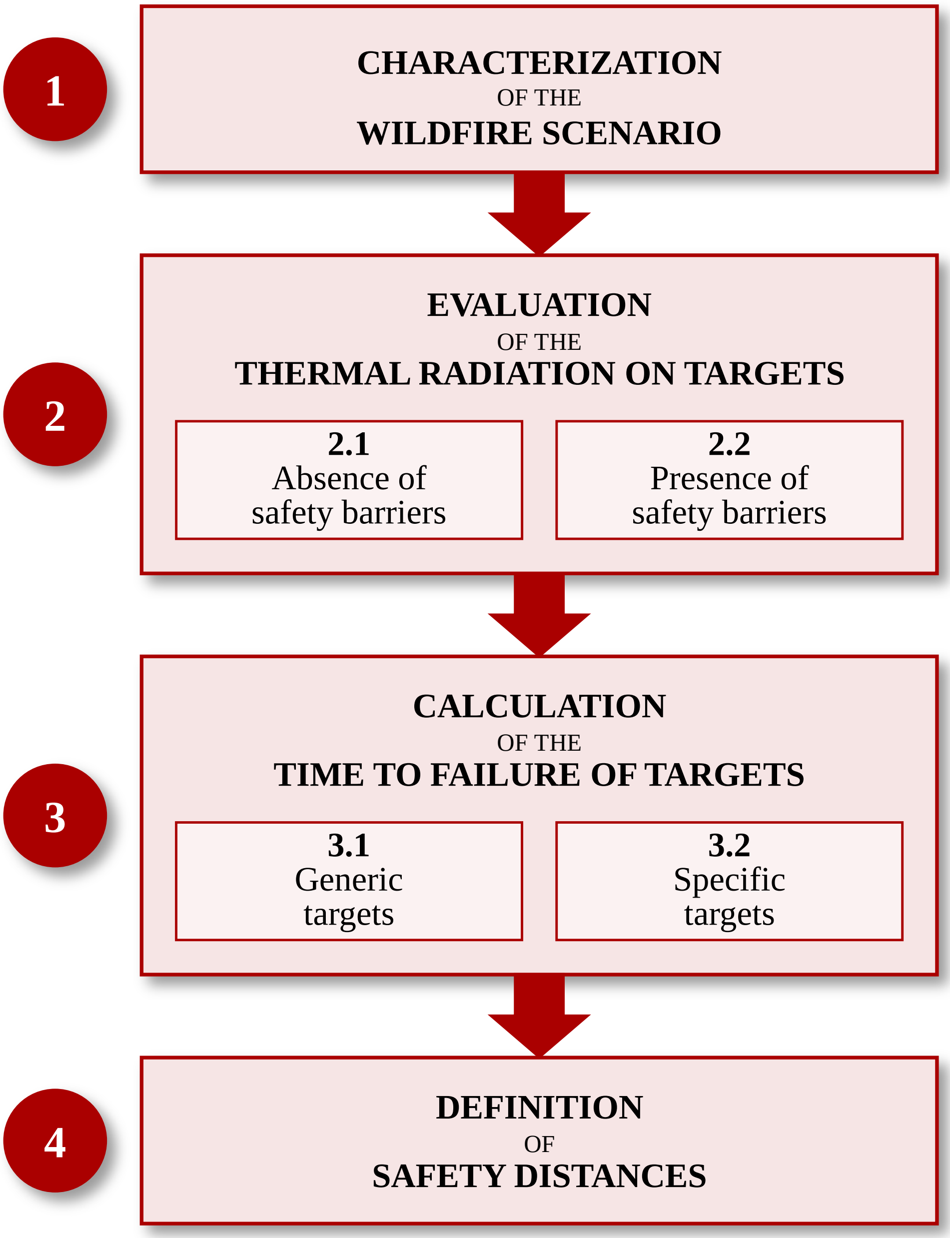

Figure 3.1. Flowchart of the methodology developed for the definition of safety distances to ensure tank integrity in the case of wildfire scenarios.

3.2.1 Step 1: Characterization of the wildfire scenario

The first step of the methodology aims at the characterization of the wildfire scenarios in terms of flame shape, dimension, and fire emissive power, providing the inputs for the evaluation of the thermal radiation (Step 2 in Figure 3.1).

Dealing with wildfires, thermal radiation and convection represent the main energy vectors impacting structures and causing potential damages [17,18]. When considering industrial installations, clearance areas where no vegetation is allowed are usually present at the plant boundary for safety and security reasons. This makes unlikely the direct contact of equipment items with flames from a wildfire. Thus, the contribution of convection is usually negligible, and wildfires represent a distant source of radiation for industrial items. For this reason, the heat transfer between the wildfire and industrial equipment can be evaluated through the solid flame model approach [19], as suggested in previous studies [17,18,20–22]. Hence, the wildfire is modelled as a solid body of defined shape, dimensions, and emissive power. Thus, the characterization of the wildfire scenario according to these parameters is the aim of the present step of the methodology.

A multitude of software tools is present in the literature for wildfire behaviour modelling [23], such as FARSITE [24], PROMETHEUS [25], and SPARK [26]. These models allow for the characterization of the fire spread throughout vast areas, incorporating information on the fire spread rate, fire intensity, and flame geometry. To perform the evaluation, these tools require several specific inputs related to the type of burning vegetation, the slope of the terrain, distribution and load of the fuel and weather variables (e.g., temperature, relative humidity, wind.), just to mention a few. Thus, the results obtained from such simulations are extremely specific from the point of view of the location and of the meteorological condition. For this reason, the use of such tools is out of the scope of the present study, which aims at providing a generalized approach to the definition of safety distances. Moreover, wildfire behaviour may change considerably when the fire fronts approach the edge of the vegetation at the wildland-human interface [6]. Indeed, local variations in the type and spatial distribution of fuel play an important role in the fire spread and structure damage [5]. Thus, wildfire models show some limitations when applied to simulate fire fronts approaching an industrial site.

The characterization of the emissive power E depends on the fire intensity and the radiative fraction of the heat released by the fire. According to the literature, the fire intensity can be represented by Byram's fireline intensity I_B, firstly introduced by Byram in 1959 [27]. The fireline intensity I_B strongly depends on the type of burning vegetation, the fuel distribution, and other factors that influence the wildfire spread such as the weather conditions (e.g., air temperature, wind speed) and the features of fuel and terrain (e.g., fuel moisture content, slope steepness) [27–29]. Similarly, the radiative fraction is influenced by several factors as well, such as the size and the shape of the burning area [27]. Therefore, the radiative fraction may vary considerably, and Byram suggests that a plausible range is between 3% and 30% of the total heat generated [27]. All considered, the fireline intensity and the radiative fraction are characterized by intrinsic variability, and their estimation is affected by uncertainty. For these reasons, flawed results may be obtained basing the definition of safety distances on these variables. Thus, a different approach was followed in the present study for the assessment of emissive power. Specifically, the wildfire front was represented as a grey body and the Stefan-Boltzmann law was used for the evaluation of the emissive power E, as in several previous studies [18,20,30]. The emissive power E [W/m^2] is therefore calculated as:

$$E = \varepsilon_f \cdot \sigma \cdot T_f^4 \qquad \text{Eq. 3.1}$$

where ε_f is the flame emissivity [dimensionless], T_f is the flame temperature [K] and σ is the Stefan-Boltzmann constant (equal to 5.67 10^{-8} W/m^2K^4). Despite the high variability of the flame temperature and of the emissivity across the flame profile [31,32], some conservative assumptions can be introduced for their evaluation. Specifically, a fire black body temperature of 1200 K is assumed for the estimation of the fire emissive power. Indeed, this assumption is considered reasonable by several authors dealing with the definition of safety distances for people and civil structures facing a wildfire front [18,20,30]. Thus, an emissive power E of around 118 kW/m^2 is conservatively assumed in the present methodology.

The flame shape and dimensions should be determined to complete the wildfire scenario characterization. In the present methodology, wildfires are modelled as a plane of sizes equal to the flame length L_f and the fire front width W_f, inclined according to the flame tilt angle θ. Figure 3.2 reports a schematization of the flame shape and of the related geometrical parameters used to model wildfire scenarios.

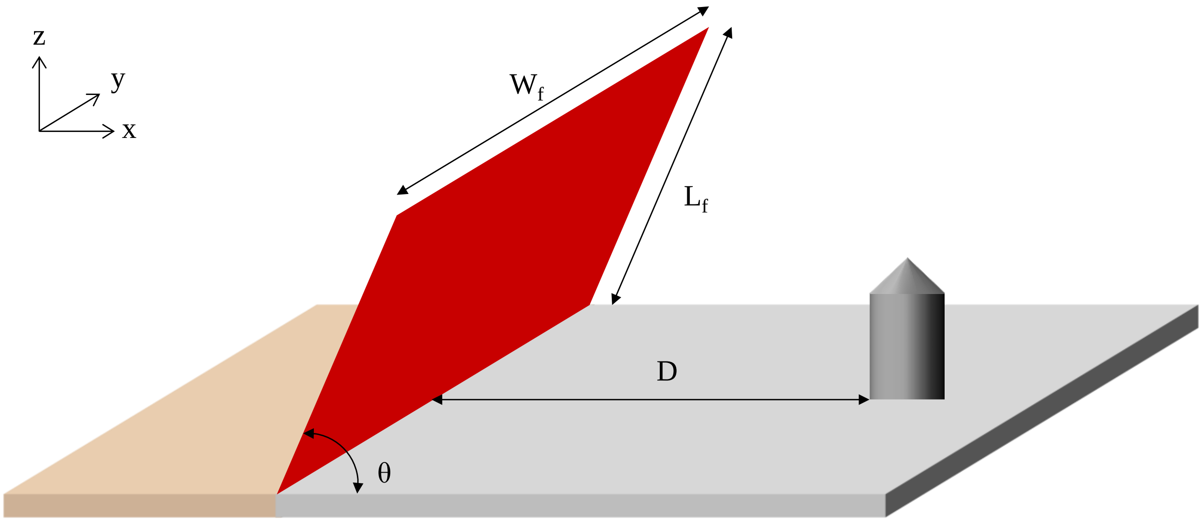

Figure 3.2. Scheme of the flame shape and definition of the geometrical parameters used to model wildfire scenarios.

The fire front width W_f depends on the terrain configuration, the fuel distribution, and the weather condition. In addition, it is also influenced by the temporal and spatial evolution of the wildfire. All these parameters are specific to a particular wildfire, and they may change during the event. Thus, a general and simple estimation of the fire front width W_f cannot be performed. Therefore, following a conservative approach, an infinite value of the fire front width W_f is used in the present methodology.

The second geometrical parameter that needs to be characterized is the flame tilt angle θ, defined as the angle between the fire front and the terrain as represented in Figure 3.2. The specific literature provides many empirical expressions for the evaluation of the flame tilt angle θ [33], mainly derived from observation and experimental studies. These expressions allow the calculation of the flame tilt angle θ based on Byram's fireline intensity I_B and the wind velocity at a given altitude (typically 10 m from the ground level), which are case-specific and may vary during the wildfire event. Hence, a generic and conservative approach is applied in the present methodology. A worst-case scenario is considered, and the flame tilt angle θ is defined as the one that maximizes the view factor at each value of the distance between the fire and the industrial targets. Thus, a changing value of the flame tilt angle θ is selected as a function of the flame length L_f and the fire-target distance D. Eventually, the value tends to 90° for long distances regardless of the flame length. The assumption is better clarified in Section 3.2.2.

The last parameter related to the flame geometry is flame length L_f. This parameter depends on several factors. Among others, the type of burning vegetation and the fire regime that is established are extremely important. In the present methodology, the flame length is defined as a function of the burning wildlands. Three main types of vegetation are identified: grasslands, shrublands, and forests/woodlands. Following the definitions established by the specific literature [34], grasslands and shrublands are surface fuels and they give rise to the so-called surface fires, namely grassfires and shrubfires. Surface fires typically feature a fast spread rate and a moderate flame length [35], with the last parameter usually lower in grassland than shrubland. When considering forests, three main fire regimes can occur [36]:

- Surface fire. It occurs when the combustion is limited to the understory fuel. In this case, the combustion is limited to the lower layer of the forest and canopies of the trees are not involved.
- Passive crown fire. It occurs when canopies of a single tree or a small group of trees are involved in the combustion, catching fire from the understory surface fire. In a passive crown fire, combustion is not maintained in the higher layer of the forest.
- Active crown fire. It occurs when the flame is sustained in both the surface fuels and the canopies. In this case, a solid wall of flame is generated and the surface and crown phases of the fire travel together.

Active crown fire represents a more severe scenario than passive crown fires and surface fires involving understory as it is characterized by higher flame length [36]. For this reason, following a worst-case scenario approach, only active crown fires are considered in the present methodology dealing with forests. Figure 3.3 report a graphical representation of the three vegetations and the related fire regimes.

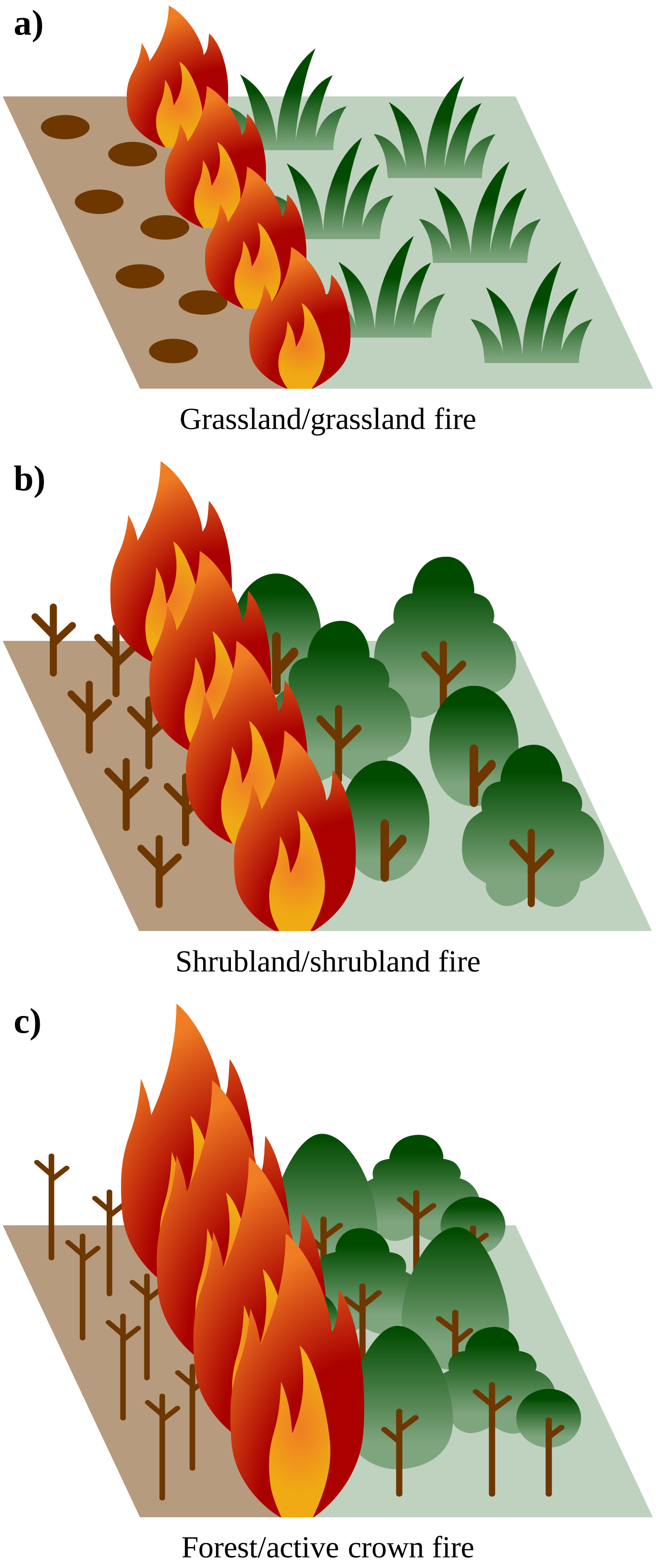

Figure 3.3. Representation of the vegetation and related type of wildfire considered in the present study.

A literature review was carried out to define typical flame length L_f for the fire regimes considered in the methodology. As for grassfires, flame length typically ranges from 3 to 7.5 meters [37–40], and Table 3.1 reports an excerpt of the specialized literature providing information on the maximum flame length reported in each reference in the case of grassfires both considering prescribed fires and wildfires. Shrubfires, instead, feature flame lengths L_f ranging from 3 to 13 meters [32,41–44], as reported in Table 3.2. In both cases, the upper value of each range was considered to conservatively characterize the flame length L_f for grassfires and shrubfires. Concerning crown fire, the literature suggests that the flame length L_f is correlated to the average height of the vegetation H_v [18,21]. Indeed, flame length L_f can reach up to 3 times the height of the vegetation H_v according to Butler [21] while Zarate provides values ranging from 2.5 to 3.5 times the vegetation height for trees higher than 4 meters [18]. Conservatively, a value of 3.5 times the height of the vegetation is assumed in the present methodology.

Table 3.1. Maximum flame length for grassfires reported in specialized literature both considering prescribed fires and wildfires.

Authors	**Year**	**Ref.**	**Maximum flame length[1] [m]**
Clark	1983	[37]	4.2
Cruz et al.	2018	[38]	4.5
Cheney and Gould	1995	[39]	7.5
Sneeuwjagt and Frandsen	1977	[40]	3

[1] not considering possible outliers

Table 3.2. Maximum flame length for shrubfires reported in specialized literature both considering prescribed fires and wildfires.

Authors	**Year**	**Ref.**	**Maximum flame length[1] [m]**
Catchpole et al.	1998	[41]	13
Vega et al.	1998	[42]	6.5
Fernandes et al.	2009	[43]	3
Cruz et al.	2011	[32]	7-8
Van Wilgen et al.	1985	[44]	4.5

[1] not considering possible outliers

In summary, Eq. 3.2 reports the rule adopted in the present methodology for the evaluation of the flame length L_f according to the type of vegetation present in the proximity of the plant boundary [m], where H_v is the average height of trees in the case of forests [m].

$$L_f = \begin{cases} 7.5 & \text{Grassland fire (GF)} \\ 13 & \text{Shrubland fire (SF)} \\ 3.5 \cdot H_v & \text{Crown fire (CF)} \end{cases} \qquad \text{Eq. 3.2}$$

3.2.2 Step 2: Evaluation of the thermal radiation on targets

Once the wildfire scenario is characterized, the heat load on the target surface should be calculated (Step 2 in Figure 3.1). Dealing with fires at Wildland-Industrial Interfaces (WII), the heat load on the target is represented only by the thermal radiation, as introduced in the previous section (see Section 3.2.1). Indeed, the presence of a clearance area around the industrial installation makes direct contact with flame unlikely. Two different approaches are described in the following sections. Specifically, Section 3.2.2.1 describes the methodology that should be followed to calculate the thermal radiation *I* in absence of safety barriers and shielding effects. Section 3.2.2.2, instead, allows considering the presence of firewalls and spray systems. Noteworthy, other protective measures (e.g., fireproofing) can be applied to industrial items to protect them from fire exposure. Despite this, the methodology can be modified to accommodate for the inclusion of safety barriers rather than providing a comprehensive discussion of all possible safety barriers that can be implemented.

3.2.2.1 Step 2.1: Absence of safety barriers

The thermal radiation that reaches the target surface as a consequence of fire exposure in absence of safety barriers can be calculated through the solid flame model approach [19].

$$I = E \cdot F \cdot \tau_a \qquad \text{Eq. 3.3}$$

where I is the thermal radiation on the target surface [W/m^2], *E* is the emissive power of the wildfire calculated according to Eq. 3.1 [W/m^2], τ_a is the atmospheric transmissivity [dimensionless], and *F* is the view factor between the target and the flame [dimensionless].

The view factor *F* is a geometrical parameter that accounts for the portion of thermal radiation emitted by the fire, namely the wildfire, and reaches the target surface. For its assessment, information on the flame shape, dimension, orientation and the relative position between the fire and the target is required. In the case of simple geometry, analytical expressions are available in the literature [45,46]. According to the geometry described in Section 3.2.1 and represented in Figure 3.2, the view factor *F* can be calculated following the equation proposed by Mudan [47]. Here, the flame tilt angle θ considered is the one that maximizes the view factor *F* at each distance *D* and each flame length L_f, as introduced in Section 3.2.1. This assumption allows for performing a conservative assessment since the maximization of the view factor is directly reflected in the thermal radiation.

Eventually, the atmospheric transmissivity τ_a takes into consideration the fraction of emitted radiation that reaches the target passing through the atmosphere. It can be calculated through an empirical correlation as a function of the carbon dioxide concentration and relative humidity [46]. To perform a general and conservative estimation, a unit value of atmospheric transmissivity is considered.

3.2.2.2 Step 2.2: Presence of safety barriers

In this section, the changes in the methodology that allows the calculation of thermal radiation accounting for the effects of firewalls and spray systems are presented.

As introduced previously, industrial sites typically have boundary walls to protect the site from intrusions by malicious people and attacks from the outside. Even if boundary walls are built with a different purpose, they can provide a shielding effect to the industrial items against fires that occur outside the plant, namely wildfires, thus working like firewalls. Indeed, firewalls are passive protective measures built to protect a target from a possible fire source [48]. Thus, firewalls provide shielding effects on the target reducing the thermal radiation received. This can be evaluated considering the reduction of the portion of fire seen from the target due to the presence of the wall. The mitigated thermal radiation can be still calculated using the solid flame model approach by modifying the view factor between the fire and the target, as reported in the following equation:

$$I_m = E \cdot F_m \cdot \tau_a \qquad \text{Eq. 3.4}$$

where I_m is the mitigated thermal radiation received by the target [W/m^2], E is the emissive power of the wildfire [W/m^2], F_m is the modified view factor that accounts for the presence of the wall [dimensionless], and τ_a is the atmospheric transmissivity [dimensionless].

The assumption used in the previous section for the atmospheric transmissivity τ_a is valid also here (i.e., $\tau_a = 1$). As for the view factor, two additional geometrical parameters should be defined: the height of the wall H_w and the distance between the wall and the target D_w. Figure 3.4 reports a schematization of the flame shape introducing also the geometrical parameters related to the characterization of the firewall. The modified view factor can therefore be calculated still using the expressions proposed by Mudan [47] by subtracting the view factor between the wall and the target $F_{w\to t}$ from those calculated between the fire and the target $F_{f\to t}$ (referred to simply as F in the previous section) as reported in the following equation:

$$F_m = F_{f\to t} - F_{w\to t} \qquad \text{Eq. 3.5}$$

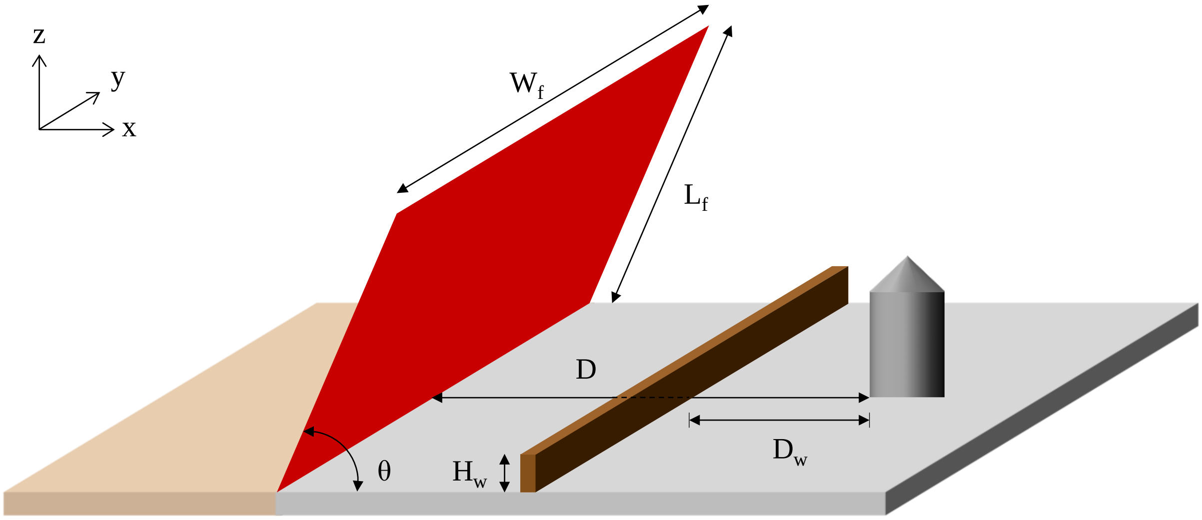

Figure 3.4. Scheme of the flame shape and definition of the geometrical parameters used to model wildfire scenarios in presence of firewalls.

Spray systems are active protective measures that can be used to keep tanks cool and avoid collapse due to fire exposure, reducing the heating effect of the thermal radiation on the tank surface [49]. Different types of spray systems can be applied to protect a target, such as sprinkler systems or water deluge systems. The effectiveness of these systems is typically described through a radiation intensity reduction, η [50–53]. Thus, the radiation intensity received by an equipment item protected by sprinklers or deluge systems can be calculated according to the following formula:

$$I_m = \eta \cdot I \qquad \text{Eq. 3.6}$$

where I_m is the mitigated thermal radiation [W/m^2], η is the reduction parameter [dimensionless], and I is the thermal radiation in absence of safety barriers calculated through Eq. 3.3.

3.2.3 Step 3: Evaluation of the time to failure

The following step of the methodology is related to the calculation of the time to failure of targets (Step 3 in Figure 3.1). As already introduced in Section 3.1, targets considered in the present work are atmospheric and pressurized tanks since storage tanks are usually located in the proximity of the plant boundary resulting to be the most vulnerable pieces of equipment when considering wildfires.

Two approaches are proposed in the present methodology dealing with the evaluation of the time to failure *ttf*, both based on the correlation provided by Landucci et al. [14]. The first aims at providing a specific value of the time to failure *ttf* considering some detailed information on the tank (Section 3.2.3.1). The second provides a more general and conservative value simply based on the type of target, namely atmospheric and pressurized tanks (Section 3.2.3.2).

3.2.3.1 Step 3.1: Specific assessment of the time to failure

The specific assessment of the time to failure *ttf* can be obtained by applying the expressions proposed by Landucci et al. [14]. These correlations were developed through the application of a lumped model to an extended set of tanks. The lumped model assesses the response of storage tanks to fire exposure accounting for the thermal weakening, thus comparing mechanical stresses on the vessel with the admissible tensile strength at the shell temperature. Starting from the results of the model, conservative correlations for the calculation of the time to failure *ttf* were derived for atmospheric cone roof tanks and pressurized horizontal vessels, reported in Eq. 3.7 and Eq. 3.8 respectively. The *ttf* is evaluated as a function of the thermal radiation I [kW/m^2] received by targets and its volume V [m^3], and the result is expressed in seconds.

$$\ln(ttf) = -1.13 \cdot \ln(I) - 2.67 \cdot 10^{-5} \cdot V + 9.9 \qquad \text{Eq. 3.7}$$

$$\ln(ttf) = -0.95 \cdot \ln(I) + 8.845 \cdot V^{0.032} \qquad \text{Eq. 3.8}$$

It is worth mentioning that the correlation for cone roof atmospheric tanks (Eq. 3.7) was developed for tanks featuring a volume ranging from 25 and 17500 m^3. In the case of pressurized horizontal vessels (Eq. 3.8), volumes between 5 and 250 m^3 and design pressure in the range of 1.5-2.5 MPa were considered. The correlations were developed without considering protective measures (e.g., fireproofing coatings) on targets.

3.2.3.2 Step 3.2: Generic assessment of the time to failure

Detailed information on tanks, such as their volume, is typically available only in advanced design stages of new industrial installations or for existing plants. Thus, the generic correlations for the calculation of the *ttf* are useful to broaden the applicability of the methodology to the earliest stages of design. Hence, starting from correlations developed by Landucci et al. [14], conservative equations were obtained for the time to failure *ttf* which account only for the type of equipment and the thermal radiation I received by the target, regardless of the volume. The correlation for atmospheric tanks is reported in Eq. 3.9, while that for pressurized vessels is reported in Eq. 3.10. Symbols, units of measure and limit of applicability are the same reported for the equations proposed in Section 3.2.3.1.

$$\ln(ttf) = -1.13 \cdot \ln(I) + 9.43 \qquad \text{Eq. 3.9}$$

$$\ln(ttf) = -0.95 \cdot \ln(I) + 9.31 \qquad \text{Eq. 3.10}$$

3.2.4 Step 4: Definition of safety distances

The last step of the methodology (Step 4 in Figure 3.1) concerns the calculation of safety distances. Safety distances (i.e. the separation distance between a tank and the vegetation that may fuel the fire) are a measure aimed at ensuring the integrity of a piece of equipment (storage tanks in this case). In the case of fire, safety distances may be related to the time to failure *ttf* calculated for the specific scenario of interest, as suggested in previous studies [54,55].

According to Step 2 of the present methodology, the thermal radiation depends on the view factor, which in turn is a function of the distance between fire and targets (see Section 3.2.2). Then, Step 3 allows calculating the time to failure of targets based on the thermal radiation (see Section 3.2.3). Thus, combining the results of these two steps it is possible to obtain a relationship between the time to failure *ttf* and the fire-target distance *D*. The safety distance can be therefore defined as the value of distance for which the failure of the tank is avoided. Hence, it is necessary to define a reference time *RT* to be compared with the time to failure. Eventually, safety distances can be calculated as the minimum distance between tanks and vegetation that satisfies the following condition:

$$ttf \geq RT \qquad \text{Eq. 3.11}$$

The reference time *RT* should be chosen among the characteristic times of the scenario being considered. In the specific case of fire exposure, characteristic times that can be considered are the exposure time to the fire t_e and the response time of emergency teams t_r [54,55]. Specifically, the minimum among these two values should be considered.

$$RT = \min\left(t_e, t_r\right) \qquad \text{Eq. 3.12}$$

The exposure time t_e represents the amount of time for which the tank is exposed to the thermal radiation from the wildfire front. It depends on the spread rate of the fire and its residence time. Both these parameters are influenced by several factors such as the type of burning vegetation and its characteristics, the slope of the terrain, and the weather conditions to mention a few. As discussed in Section 3.2.1, these factors are extremely site-specific and do not allow for a general estimation of the exposure time. In addition, limited information is available in the specific literature regarding the wildfire residence time [56] and values typically refer to wildfires which spread through uniformly distributed vegetation. This is not the case of fire front approaching industrial plants since the fire occurs at the edge of the vegetation, and this condition affects both the fire spread and residence time [28,57]. Despite this, experienced firefighters suggested that the exposure time has typically an upper limit of 15 minutes even when considering fires at the edge of the vegetation. Hence, a value of 15 minutes is considered in the present methodology as the exposure time to perform a conservative assessment of the safety distances.

The response time of emergency teams t_r represents the time needed for teams to reach the site and protect the exposed tanks using firefighting equipment. Although being a site-specific parameter as the exposure time t_e, the response time is easier to obtain as it is typically reported in the emergency response plans of the facility.

Moreover, a plausible estimate of t_r can be based on current practice, technical guidelines and experience even without specific information on the plant, as in the case of early design stages of new industrial sites. Indeed, response time credibly ranges from 5 to 30 minutes [58]. The lower value can be representative of industrial plants where dedicated fire brigades are available on-site and specific safety barriers are present, such as permanent fire monitors. The upper value is credible when considering isolated depots (e.g., fuel depots for the distribution of fuel to service stations) or small industrial sites where no internal firefighting teams are present.

Summing up, once the fire scenario of interest is characterized according to Section 3.2.1 (Step 1), the thermal radiation *I* is evaluated as a function of the distance *D* (Step 2) applying the procedures reported in Sections 3.2.2.1 and 3.2.2.2 respectively for the case of absence and presence of safety barriers. The time to failure *ttf* can be then evaluated by performing the specific assessment described in Section 3.2.3.1 or the generic one reported in Section 3.2.3.2. Hence, the time to failure is compared with the reference time *RT*, and the safety distance is defined as the minimum value of the distance for which the *ttf* is higher than the *RT* (procedure reported in the present section).

3.3 Case studies

Three case studies are defined and analysed in the present work. All case studies are developed to demonstrate the applicability of the developed methodology. In addition, case studies aim at highlighting the potential of both the generic assessment of safety distance and the specific one. Moreover, the reduction of the safety distances obtained by applying safety barriers is demonstrated. The case studies evaluated in the present work are the following:

- Case study 1. Definition of generic safety distances for a wide set of vegetation.
- Case study 2. Calculation of specific safety distances for a tank farm in absence of safety barriers and evaluation of the appropriateness of existing separation distances.
- Case study 3. Calculation of specific safety distances considering the implementation of firewalls and spray systems as safety barriers.

Two different reference times *RT* were selected for all case studies: 5 min and 15 min. The lower one is taken as representative of a best-case scenario the maximum response time of the emergency teams. The higher one, instead, represents the maximum exposure time to the wildfire according to the literature on the field (worst-case scenario). Eventually, details on each case study are provided in the following sections.

3.3.1 Case study 1: Generic safety distances

The first case study aims at defining generic safety distances for a wide set of vegetation. For this reason, the case study is carried out considering the absence of safety barriers (Section 3.2.2.1) and applying the generic assessment of the time to failure (Section 3.2.3.2). Thus, no details on the target considered are required out of the type: atmospheric and pressurized tanks. The vegetations considered are grassland, shrubland, and forests with an average height of the trees H_v ranging from 4 to 25 m.

3.3.2 Case study 2: Specific safety distances in absence of safety barriers

Specific safety distances in the absence of safety barriers are calculated in the second case study. Differently from the previous one, this case study was inspired by an existing tank farm composed of 22 tanks, both atmospheric and pressurized, storing hazardous substances. Figure 3.5 shows the layout of the tank farm, where green areas represent the vegetation and grey ones the industrial site.

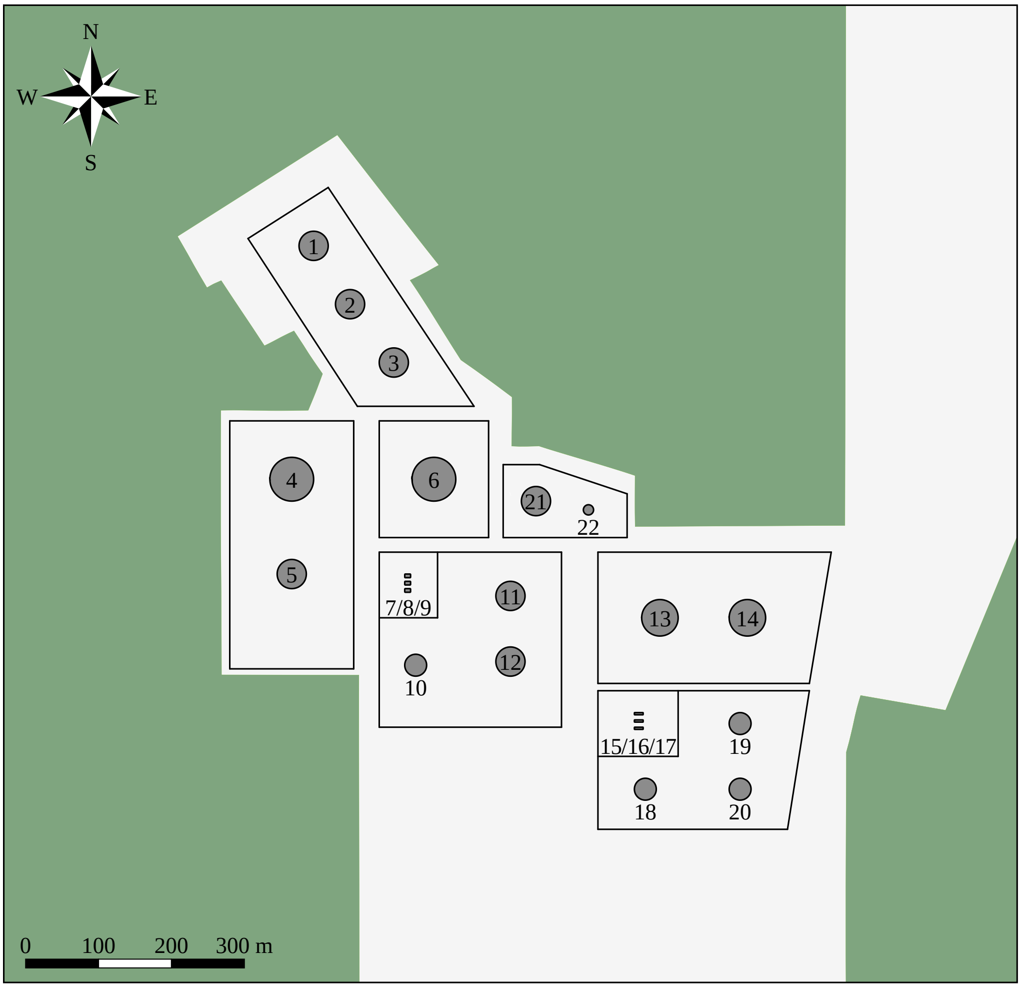

Figure 3.5. The layout of the tank farm considered as a case study for the calculation of specific safety distances in absence of safety barriers (case study 2). Green: vegetation. Grey: industrial site. Adapted from Ricci and co-workers [59].

The main features of each tank (such as type, diameter, height/length, and volume) are reported in Table 3.3. The same table also reports the actual distance of each tank from the vegetation. The tank farm is located a few kilometres from the Pacific coast in South America, at the edge of the Amazon rainforest. It is mostly surrounded by a forest, and considering the location of the case study, the NASA Jet Propulsion Laboratory [60] reports that the forest is characterized by trees with an average height of 15 meters. Accordingly, the same vegetation is assumed to perform the calculation.

Table 3.3. Main features of tanks considered in case study 2. Adapted from Ricci and co-workers [59].

Tank ID	**Type of tank**	**Diameter [m]**	**Height/Length [m]**	**Volume [m^3]**	**Actual distance [m]**
1	Atmospheric	40	10	12566	90
2	Atmospheric	40	8	10053	65
3	Atmospheric	40	8	10053	55
4	Atmospheric	60	6	16965	60
5	Atmospheric	40	10	12566	80
6	Atmospheric	60	6	16965	80
7	Pressurized	5	8	223	135
8	Pressurized	5	8	223	135
9	Pressurized	5	8	223	135
10	Atmospheric	30	8	5655	65
11	Atmospheric	40	10	12566	170
12	Atmospheric	40	10	12566	190
13	Atmospheric	50	4	7854	95
14	Atmospheric	50	4	7854	95
15	Pressurized	3	12	99	275
16	Pressurized	3	12	99	275
17	Pressurized	3	12	99	275
18	Atmospheric	30	8	5655	260
19	Atmospheric	30	8	5655	135
20	Atmospheric	30	8	5655	130
21	Atmospheric	40	8	10053	50
22	Atmospheric	14	12	1847	55

3.3.3 Case study 3: Specific safety distances in presence of safety barriers

The third case study is developed to evaluate the effectiveness of two safety barriers in the case of wildfires and the reduction of the required safety distance that is obtained when applied. A simplified case study was developed for the purpose, which is reported in Figure 3.6. The layout is made up of 4 tanks both atmospheric and pressurized, whose features are reported in Table 3.4.

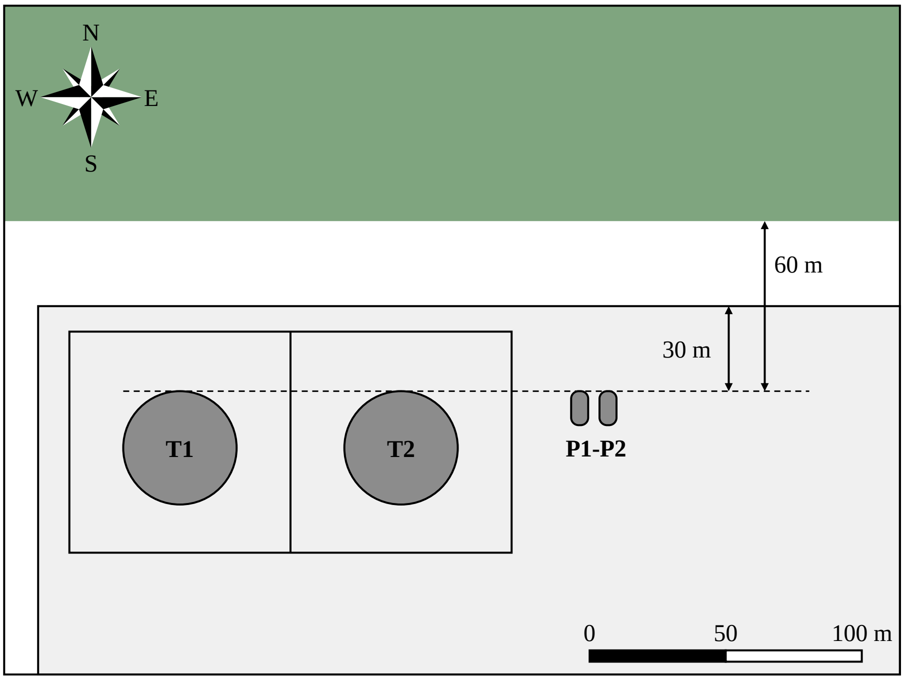

Figure 3.6. The layout of the tank farm considered as a case study for the calculation of specific safety distances in presence of safety barriers (case study 3). Green: vegetation. Grey: industrial site. Adapted from Ricci and co-workers [61].

Table 3.4. Main features of tanks considered in case study 3.

Features	**Tank ID**	
	T1-T2	**P1-P2**
Type of tank	Atmospheric	Pressurized
Diameter [m]	40	5
Length/Height [m]	10	8
Volume [m^3]	12566	223
Distance from vegetation D [m]	60	60
Distance from wall D_w [m]	30	30

The two types of barriers introduced in the previous section (Section 3.2) are both applied to the case study: firewalls and spray systems. Four cases are defined:

- Case a (wildfire). Only wildfire is considered. Thus, no safety barriers are implemented. This case represents a baseline value for the comparison of the safety distances.
- Case b (firewall). The presence of a firewall is considered. The wall is located at the plan boundary, having a distance from D_w the tank of 30 m, as reported in Figure 3.6 and Table 3.4. The wall considered in the analysis has a height H_w equal to 3 m (see Figure 3.4 for the definition of the geometrical parameters).
- Case c (spray system): The presence of a spray system is accounted for. Following the approach of previous studies [62,63], the radiation intensity reduction parameter η equal to 0.5 is considered for demonstrative purposes.
- Case d (firewall and spray system). The implementation of both the firewall and the spray system is considered. The features of the safety barriers are those presented in the previous cases.

Eventually, four different vegetations are considered for each case to evaluate the performance of the safety barriers as a function of the type of vegetation. The features of vegetation are reported in Table 3.5.

Table 3.5. Features of vegetations considered in case study 3. Adapted from Ricci and co-workers [61].

Vegetation ID	**Type of vegetation**	**Vegetation height, H_v [m]**	**Flame length, L_f [m]**
GF	Grassland	-	7.5
SF	Shrubland	-	13
CF5	Forest	5	17.5
CF15	Forest	15	52.5
CF25	Forest	25	87.5

3.4 Results

In the present section, the application of the methodology is presented. Safety distances calculated for the three case studies defined in Section 3.3 are reported. The appropriateness of actual safety distances used in current industrial practice is also evaluated.

3.4.1 Generic safety distances

The present section reports the results of the methodology for the calculation of generic safety distances applied to the first case study defined in Section 3.3.

The characterization of wildfire scenarios (Step 1 in Figure 3.1) is already developed in the definition of the case study as reported in Section 3.3.1. The thermal radiation on targets was evaluated for each wildfire scenario through Eq. 3.3, following the procedure described in Section 3.2.2.1 (Step 2 in Figure 3.1). Figure 3.7 reports the thermal radiation as a function of the distance between wildfire and targets for vegetations considered in the case study. Clearly, the thermal radiation on the tank surface increases with the increases of the vegetation height H_v and therefore of the flame length L_f.

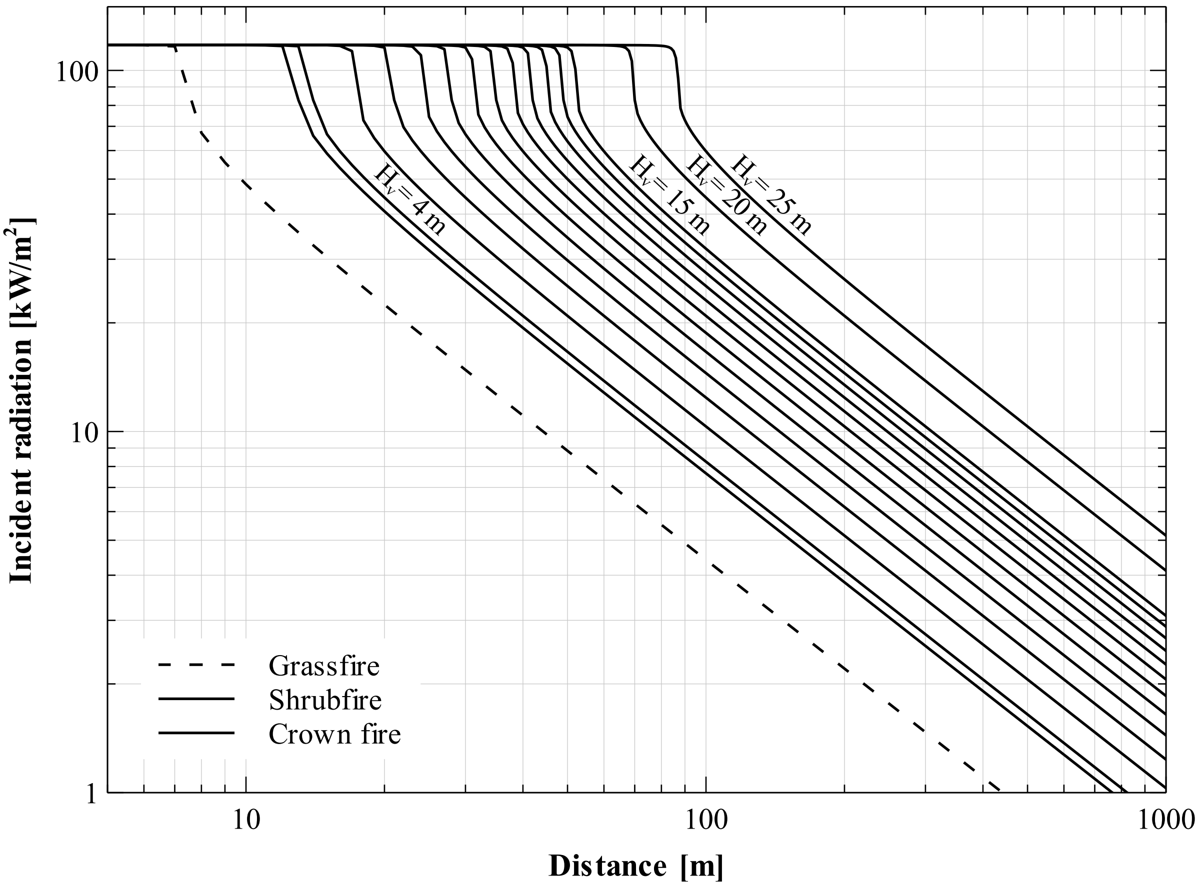

Figure 3.7. Incident radiation as a function of the distance for several vegetations in absence of safety barriers (Section 3.2.2.1). Adapted from Ricci and co-workers [64].

The procedure continues with the calculation of the time to failure of tanks (Step 2 in Figure 3.1). The generic approach for the assessment of the time to failure is followed (see Section 3.2.3.2) as required for the definition of generic safety distances. Thus, Eq. 3.9 and Eq. 3.10 are respectively applied considering the type of target and the incident radiation obtained in Figure 3.7. Hence, the time to failure as a function of the distances is obtained, and results are reported in Figure 3.8 for atmospheric tanks and Figure 3.9 for pressurized vessels.

A comparison of the two figures highlights that atmospheric tanks feature a lower time to failure than pressurized vessels, thus leading to a higher vulnerability to fire exposure. This can be explained by considering the structural differences between these two types of equipment items. Indeed, atmospheric tanks are characterized by a lower thickness of the shall than pressurized vessels since they have to withstand only the internal pressure generated by the liquid head. Clearly, pressurized vessels are designed to deal with higher internal pressure, thus requiring higher shell thickness. Hence, the lower thickness of atmospheric tanks leads to lower resistance to the local stresses caused by the thermal dilatation that occurs during fire exposure. Similarly, the higher thickness of pressurized vessels makes them less vulnerable to fire exposure, resulting in a higher time to failure [14,65].

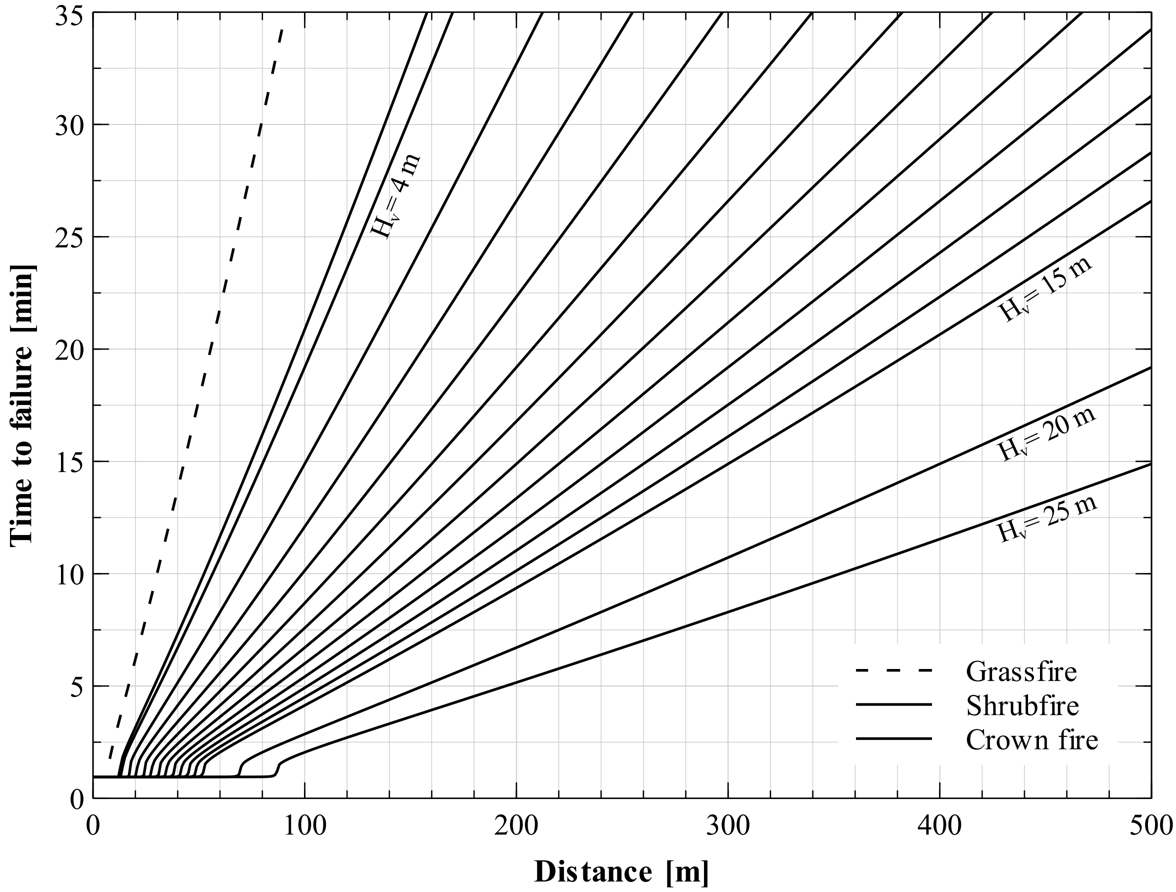

Figure 3.8. Time to failure of atmospheric tanks as a function of distance for several vegetations calculated through the generic assessment (Section 3.2.3.2). Adapted from Ricci and co-workers [64].

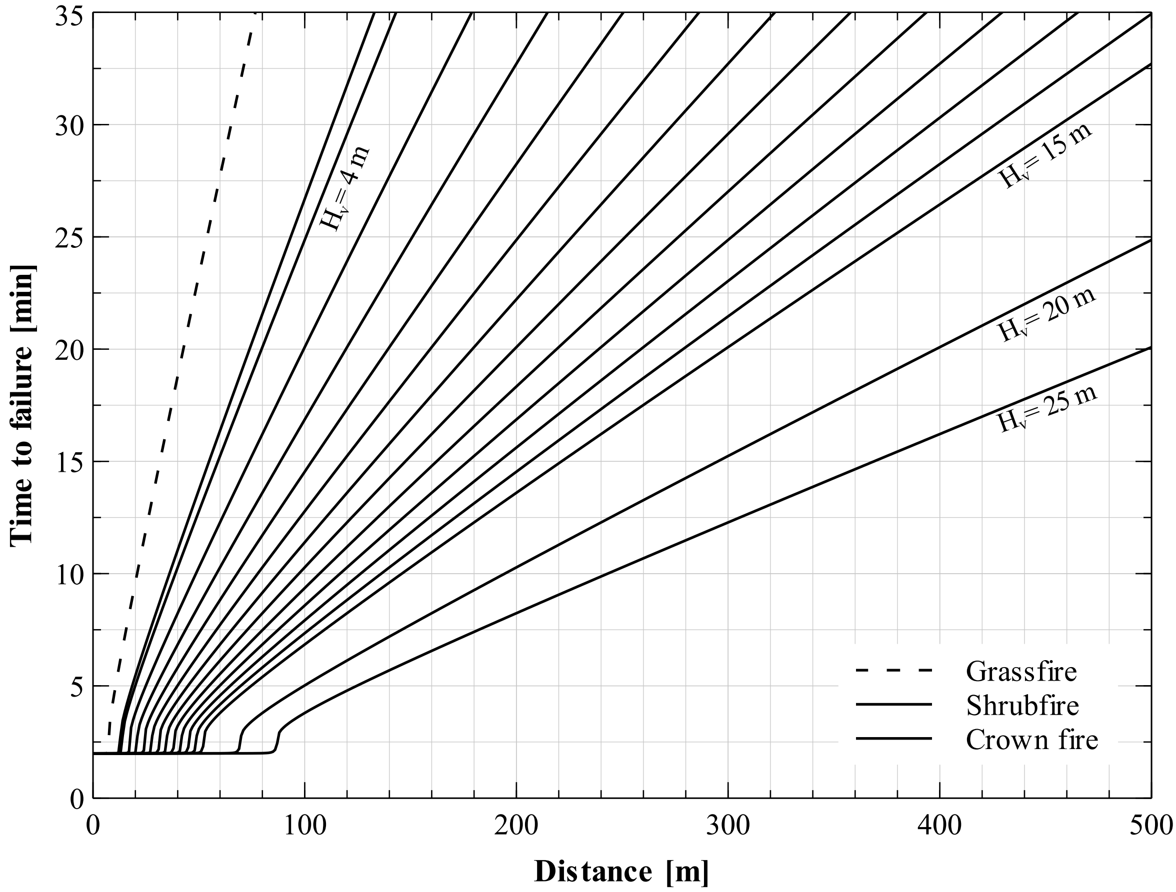

Figure 3.9. Time to failure of pressurized tanks as a function of distance for several vegetations calculated through the generic assessment (Section 3.2.3.2). Adapted from Ricci and co-workers [64].

Once the time to failures was obtained, safety distances were evaluated considering reference times *RT* of 5 min and 15 min as reported in Section 3.3. Generic safety distances were obtained following the procedure described in Section 3.2.4, thus comparing the time to failure as a function of the distance provided in Figure 3.8 and Figure 3.9 with the selected reference time. Results are reported in Figure 3.10 for a reduced set of vegetation: grassland, shrubland, and forests with average trees height of 5, 10, 15, 20 and 25 m. Clearly enough, generic safety distances for additional vegetations can be obtained following the same procedure.

Looking at the figures, a strong correlation can be observed between the reference time considered in the calculation and the resulting safety distances. More precisely, the higher the reference time, the higher the safety distances. Indeed, safety distances obtained for *RT* = 15 min (see Figure 3.10-a) are quite higher than those obtained for *RT* = 5 min (see Figure 3.10-b), even if the coefficient of proportionality is less than one.

Moreover, safety distances are also strongly influenced by the fire scenario considered. This influence can be attributed to the effect of flame length L_f, and crown fires may require safety distances of one order of magnitude higher than surface fires. Clearly enough, the higher vulnerability of atmospheric tanks with respect to pressurized vessels also affects the safety distances, which are therefore greater in the case of atmospheric equipment items.

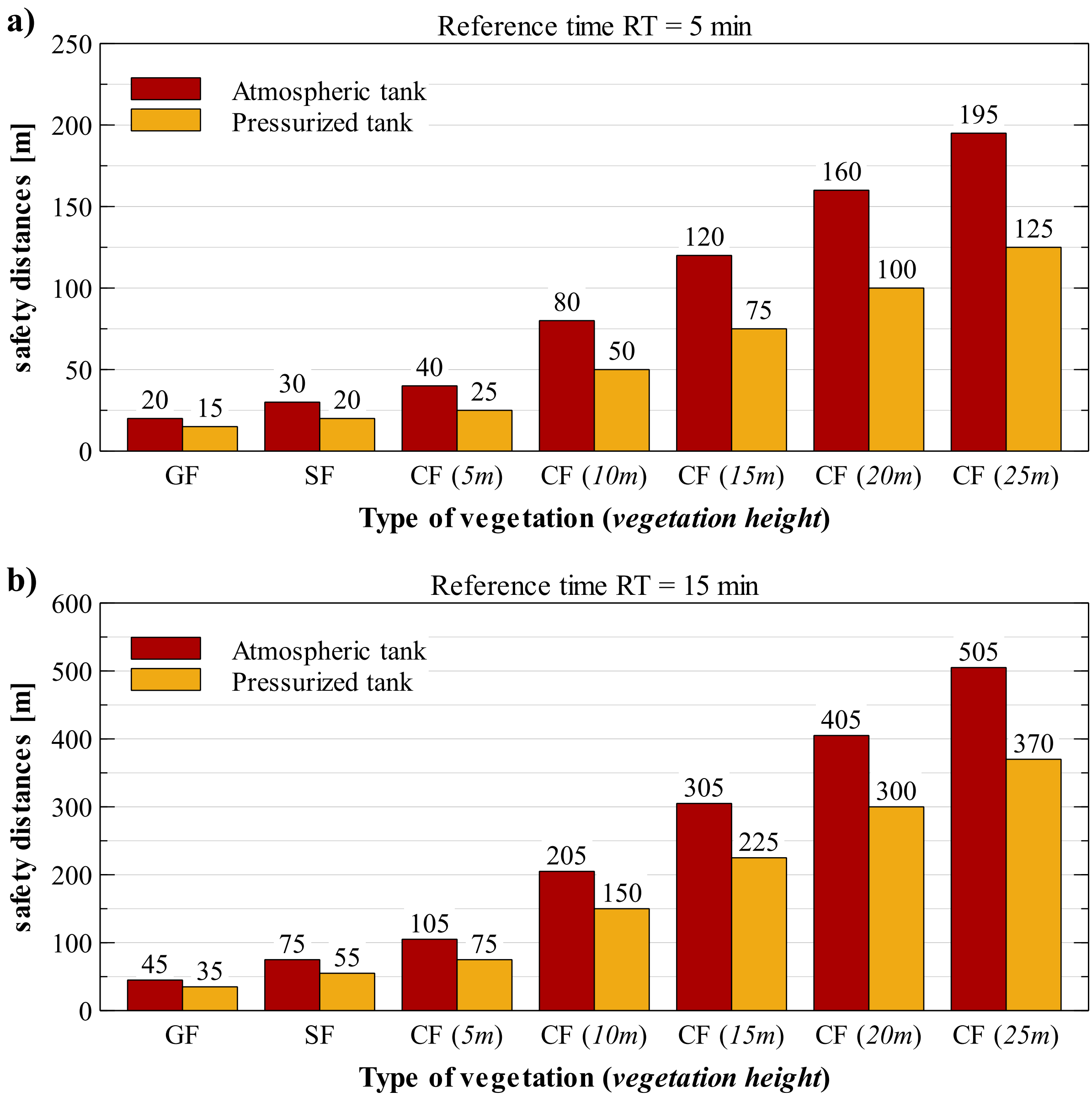

Figure 3.10. Generic safety distances considering a reference time of (a) 5 minutes and (b) 15 minutes. Values are rounded to the next multiple of 5. GF: Grassfire. SF: Shrubfire. CF: Crown fire.

3.4.2 Specific safety distances in the absence of safety barriers

The present section reports the results of the second case study defined in Section 3.3. The case study aims to derive specific safety distances in absence of safety barriers for a defined layout and to compare the obtained safety distance with the existing clearance areas present in the layout.

As already discussed in Section 3.2.3.2, generic safety distances are derived to allow the definition of appropriate clearance areas in the early design stages of new plants. Thanks to the conservative approach used in their definition, generic safety distances also represent a valuable tool to perform a preliminary screening in existing plants. Indeed, tanks cannot be threatened by the thermal radiation from the wildfire when they feature a distance from the vegetation higher than the generic safety distance related to the specific case under analysis. Thus, no specific assessment is needed for these equipment items, and they can be excluded from further evaluations. This approach is therefore applied to the second case study. Generic safety distances (*GSD*) related to atmospheric and pressurized items exposed to a crown fire deriving from trees of height equal to 15 meters are compared to the existing separation distances provided in Table 3.3. The comparison is carried out considering both the reference time of interest (5 min and 15 min), and the results are reported in Table 3.6. Tanks that result in a safe condition are marked with ✓, while tanks which seem to be affectable and require specific assessment are marked with ✗.

Table 3.6. Identification of affectable tanks based on the generic safety distances (GSD) obtained in Section 3.4.1 and the actual distance from the vegetation.

Tank ID	**Type of tank**	**Actual distance [m]**	**RT=5 min**		**RT=15 min**	
			GSD [m]	**Safe?**	**GSD [m]**	**Safe?**
1	Atmospheric	90	120	✗	305	✗
2	Atmospheric	65	120	✗	305	✗
3	Atmospheric	55	120	✗	305	✗
4	Atmospheric	60	120	✗	305	✗
5	Atmospheric	80	120	✗	305	✗
6	Atmospheric	80	120	✗	305	✗
7	Pressurized	135	75	✓	225	✗
8	Pressurized	135	75	✓	225	✗
9	Pressurized	135	75	✓	225	✗
10	Atmospheric	65	120	✗	305	✗
11	Atmospheric	170	120	✓	305	✗
12	Atmospheric	190	120	✓	305	✗
13	Atmospheric	95	120	✗	305	✗
14	Atmospheric	95	120	✗	305	✗
15	Pressurized	275	75	✓	225	✓
16	Pressurized	275	75	✓	225	✓
17	Pressurized	275	75	✓	225	✓
18	Atmospheric	260	120	✓	305	✗
19	Atmospheric	135	120	✓	305	✗
20	Atmospheric	130	120	✓	305	✗
21	Atmospheric	50	120	✗	305	✗
22	Atmospheric	55	120	✗	305	✗

According to Table 3.6, several tanks have an actual distance higher than the generic safety distance when considering a reference time of 5 min. Among these, only pressurized vessels 15, 16, and 17 are not affected by the thermal radiation from the wildfire even considering 15 min as the reference time. Thus, these equipment items will not be further considered in the following.

As defined in Section 3.3.2, the industrial site is surrounded by a forest, and trees have an average height H_v of 15 m. Thus, the curve corresponding to such height should be selected in Figure 3.7. For the sake of clarity, the same graph is reported in Figure 3.11 highlighting in red the incident radiation resulting from the vegetation under analysis.

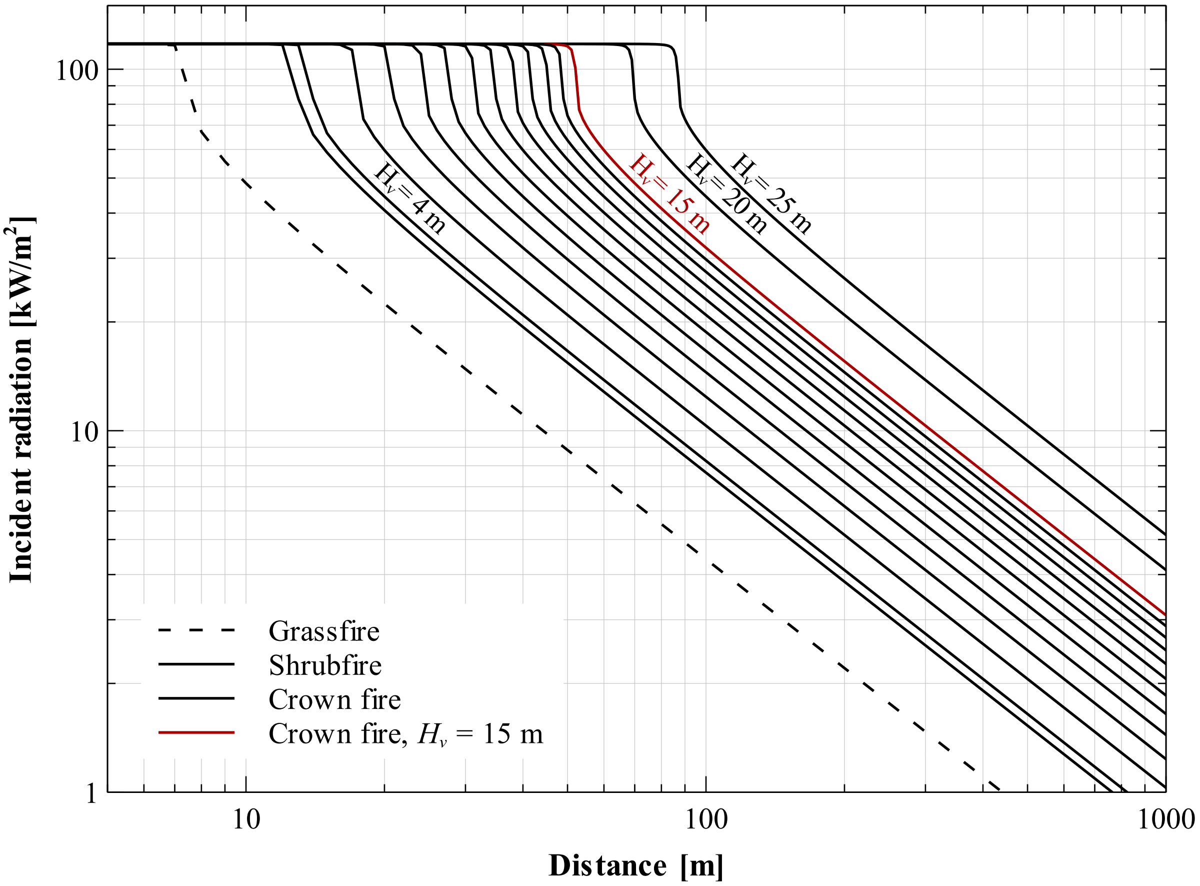

Figure 3.11. Detail of Figure 3.7 with highlighted the incident radiation related to vegetation considered for the present case study (case study 2).

The time to failure was then calculated by the specific assessment described in Section 3.2.3.1. Thus, Eq. 3.7 and Eq. 3.8 were used for atmospheric and pressurized tanks respectively. The time to failure as a function of the distance is reported in Figure 3.12 for the vulnerable tanks of the case study identified in Table 3.6. Clearly enough, atmospheric tanks are more vulnerable than pressurized vessels as already highlighted in the previous section. In addition, Figure 3.12 shows that atmospheric tanks featuring lower volumes result in higher times to failure. Thus, the vulnerability of atmospheric tanks increases with the increase of volume.

Pressurized tanks 7, 8, and 9 result in a time to failure always higher than 5 minutes, as shown in Table 3.6. This represents an extreme situation in which the thermal radiation from the wildfire does not represent a threat to the integrity of the tank, resulting in a null value of safety distance. Despite this, it is worth mentioning that a separation distance should be maintained between the vegetation and the tank to avoid flame impingement.

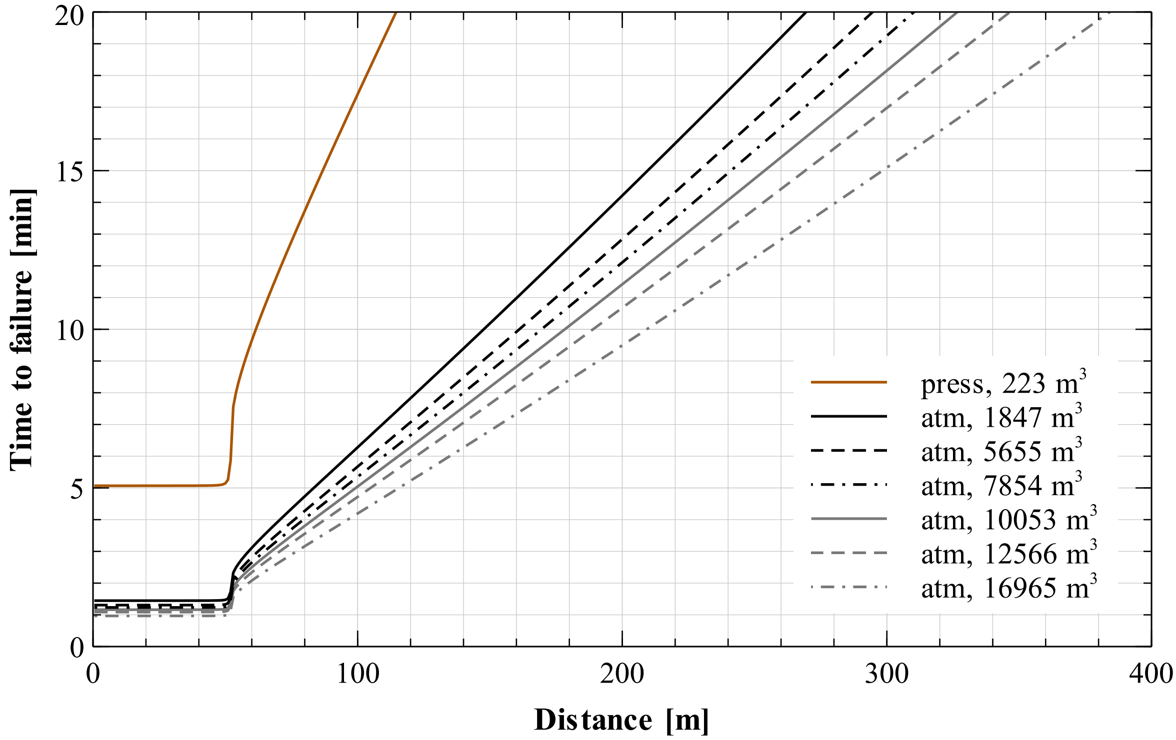

Figure 3.12. Time to failure as a function of the distance calculated through the specific assessment (Section 3.2.3.1) for tanks retrained in the analysis according to Table 3.6. Adapted from Ricci and co-workers [59].

Safety distances are then evaluated comparing the time to failures in Figure 3.12 with the reference times defined in Section 3.3. The results of the calculations are reported in Table 3.7. The trend of safety distances reproduces the same described for the generic safety distances in Section 3.4.1. Specifically, atmospheric tanks require higher safety distances than pressurized vessels and safety distances increase with the increase of the reference time.

Table 3.7. Specific safety distances in absence of safety barriers for tanks of case study 2 (see Section 3.3.2). N.F.: Failure not accounted for in the specific safety distance assessment, i.e., actual distance higher than safety distance.

Tank ID	**Safety Distance (m)**	
	RT=5 min	**RT=15 min**
1, 5	105	270
2, 3, 21	100	254
4, 6	116	299
7, 8, 9	N.F.	N.F.
10	91	230
11, 12	N.F.	270
18	N.F.	N.F.
19, 20	N.F.	230
13, 14	95	242
22	84	210

To better visualize the safety distances and to compare them with existing clearance areas, Figure 3.13 shows safety distances overlapped with the layout of the case study under analysis (case study 2). By this procedure, the appropriateness of the existing separation distances can be assessed. Looking at the figure, existing distances result inadequate to protect most of the tanks when considering a reference time of 5 minutes. Indeed, no additional tanks withstand the wildfire scenario after the specific assessment with respect to those already identified in Table 3.6. Moreover, the increase in the reference time (15 minutes) leads to an even worse situation where only pressurized tanks and atmospheric tank 18 are protected. Looking at the figure, it is clear the extensive presence of vegetation within the safety area. Hence, the existing separation distances in the layout are unable to avoid the failure of the tanks, allowing the spread of wildfire inside the industrial installation. Therefore, it is necessary to take additional safety measures to protect the tanks.

Figure 3.13. Comparison between specific safety distances in absence of barriers and actual distances in the layout considering two reference times: 5 min (yellow line) and 15 min (red line). Green: forest. Grey: industrial site. Adapted from Ricci and co-workers [59].

Since the majority of the tanks are unsafe, it is important to identify the most vulnerable ones towards which to direct prioritary protection actions. Actually, the present methodology can be used to define a vulnerability ranking of the equipment items in a given layout. The ranking is obtained sorting tanks in a decreasing order with respect to time to failure, and the time to failure is evaluated considering the actual distance from the vegetation. The ranking obtained by applying the procedure to the case study under analysis is reported in Figure 3.14. According to the results, tanks 21, 3, and 4 are the most vulnerable ones. This type of analysis allows supporting decision-makers in the identification of the more vulnerable items, highlighting the tanks which require additional safety measures with higher priority. Safety measures should be aimed at increasing the time to failure of the tanks, making them less vulnerable in the case of fire exposure. Moreover, an effective emergency plan in the case of wildfire can be defined based on the results of the analysis. Indeed, priority in the intervention should be addressed toward the most vulnerable tanks, thus reducing the response time, and therefore decreasing the risk of escalation.

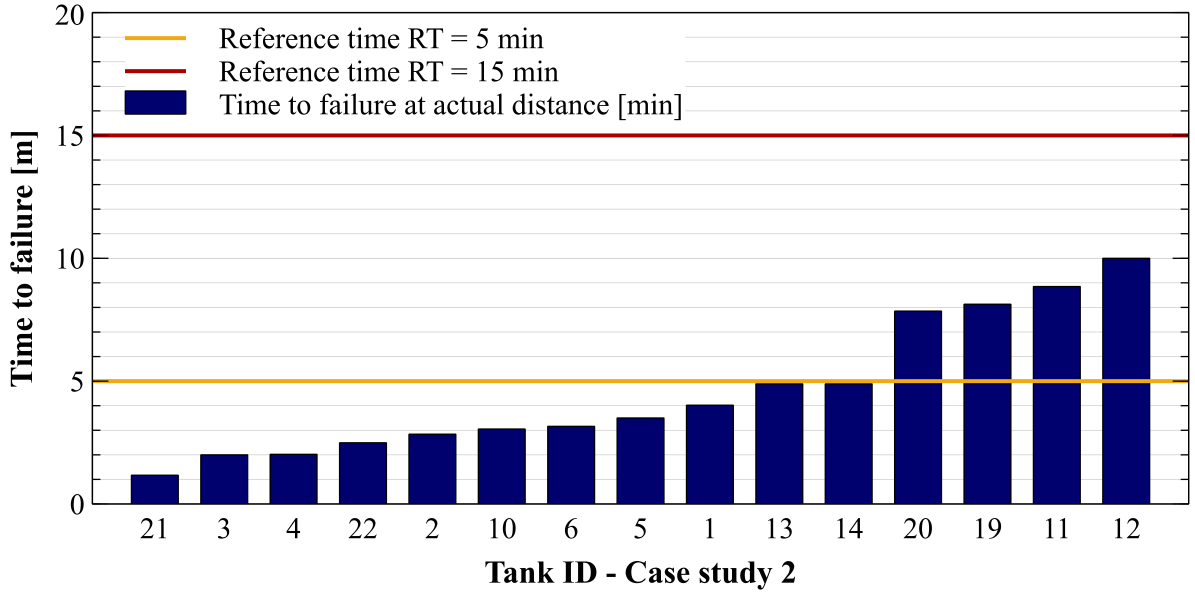

Figure 3.14. Vulnerability ranking of tanks based on time to failure calculated according to the actual distance in the layout and the wildfire scenario defined in Section 3.3.2.

3.4.3 Specific safety distances including safety barriers

The present section reports the results of the third case study defined in Section 3.3.3. The case study aims at evaluating the effectiveness of safety barriers in the protection of tanks in the case of wildfire scenarios, considering the reduction of safety distances obtained with their implementation. As for the second case study (see Section 3.4.2), generic safety distances calculated in Section 3.4.1 are used as a preliminary screening tool to identify tanks vulnerable to the wildfire scenarios considered in the case study. Results are reported in Table 3.8. Tanks that feature an actual distance higher than the generic safety distance are marked with ✓, while tanks which may be affected by the flame radiation are marked with ✗. As reported in the table, all tanks considered in the layout feature an actual distance from the flame front higher than the generic safety distance in the case of grassfires. Thus, grassland is not further considered in the following.

Table 3.8. Tanks that may be damaged by wildfire based on the generic safety distances evaluated in Section 3.4.1. The actual distance from vegetation present in the layout is 60 m for all tanks (see Figure 3.6).

Reference time	**Type of vegetation**	**Atmospheric tank**		**Pressurized tank**	
		GSD [m]	**Safe?**	**GSD [m]**	**Safe?**
RT = 5 min	Grassland	20	✓	15	✓
	Shrubland	30	✓	20	✓
	Forest, H_v = 5 m	40	✓	25	✓
	Forest, H_v = 15 m	120	✗	75	✗
	Forest, H_v = 25 m	195	✗	125	✗
RT = 15 min	Grassland	45	✓	35	✓
	Shrubland	75	✗	55	✓
	Forest, H_v = 5 m	105	✗	75	✗
	Forest, H_v = 15 m	305	✗	225	✗
	Forest, H_v = 25 m	505	✗	370	✗

The characterization of the wildfire scenario (Step 1 in Figure 3.1) is performed through the definition of the vegetation considered in the case study (see Section 3.3.3 for details). Figure 3.15 shows the incident radiation on the target surface as a function of the fire-target distance D and the safety measures applied to the case study for (*a*) shrubland fire, (*b*) crown fire with tree height of 5 m, (*c*) crown fire with tree height of 15 m, and (*d*) crown fire with tree height of 25 m. Noteworthy, the incident radiation is reported starting from 30 m, that is the distance between tanks and the boundary wall. Indeed, it is considered that no vegetation is present within the industrial site.

Looking at Figure 3.15, some preliminary results can be obtained on the features of the safety barriers considered in the analysis. The baseline value of the incident radiation obtained in absence of safety barriers (red lines) is also reported. The reduction of the incident radiation obtained by implementing the firewall (green lines) increases with the increase of the distance. Moreover, firewalls are more effective when used with wildfires that feature lower flame lengths, as can be observed by comparing the top and bottom panels of Figure 3.15. For instance, the reduction of the incident radiation when considering a fire-target distance of 60 m is around 47% in the case of shrubland, while the value stands around 5% considering crown fire with a vegetation height of 25 m. Spray systems (blue lines) are more effective than firewalls for short distances, while an inversion of the trend can be observed for long distances. Moreover, the distance at which spray systems become less effective than firewalls increases as the flame length increases, following the results derived for firewalls. Clearly, the implementation of both safety measures (yellow line) guarantees a larger reduction of incident radiation than applying each measure individually.

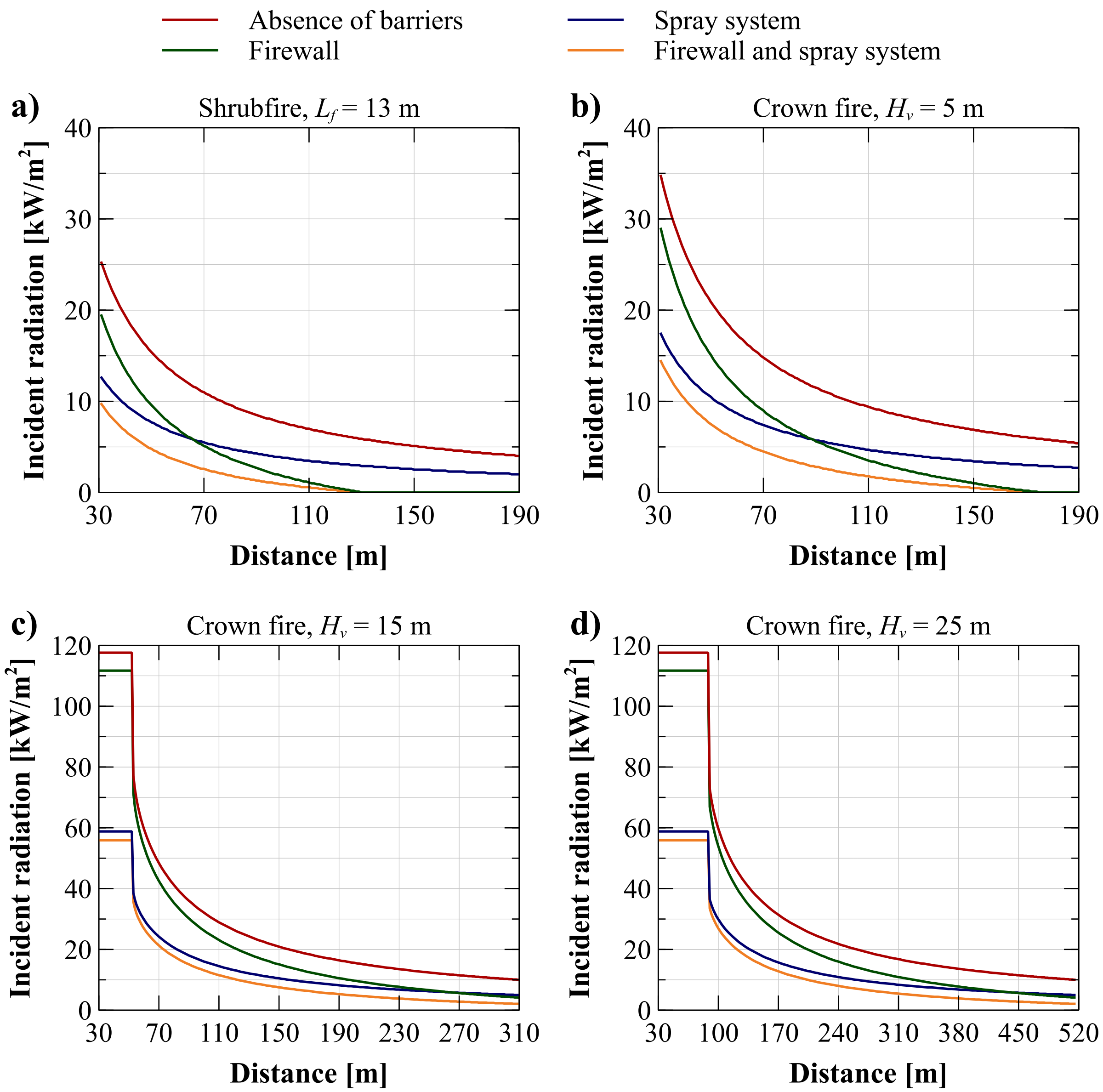

Figure 3.15. Incident radiation vs distance as a function of the type of vegetation and the presence of safety barriers.

The following step of the procedure is the calculation of the time to failure according to the specific assessment reported in Section 3.2.3.1. Results are reported in Figure 3.16 for atmospheric tanks (panels a-d) and pressurized vessels (panels e-h) considering the four types of vegetation retrained in the analysis and the implementation of the safety barriers.

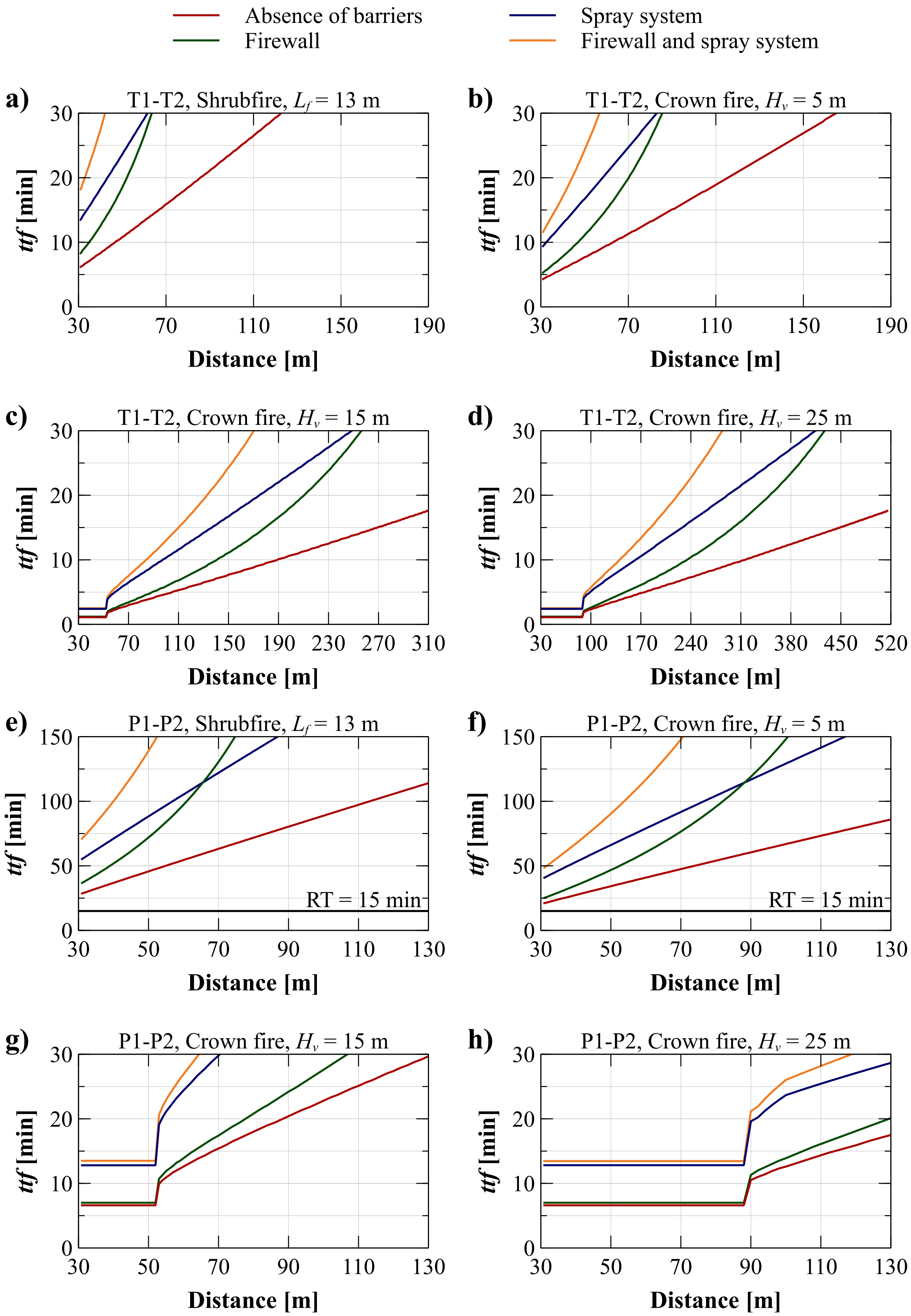

Figure 3.16. Time to failure vs distance as a function of the type of vegetation and the presence of safety barriers for atmospheric tanks (panels a-d) and pressurized vessels (panels e-h).

Then, safety distances are calculated considering both the reference times defined in the case study. Pressurized tanks have always a time to failure higher than the lower reference time (5 min), as reported in Figure 3.16. Thus, the actual distance is enough to avoid the spread of the wildfire events considered. Similar behaviour is shown by the atmospheric tanks when considering shrubfires and crown fires with trees height of 5 m. On the contrary, atmospheric tanks are vulnerable to wildfire scenarios featuring high flame length. For these wildfire events, safety distances are reported in Figure 3.17 as a function of the safety barriers implemented. The implementation of firewalls and spay systems alone does not allow to ensure the integrity of atmospheric tanks in both wildfire scenarios. Despite this, the implementation of both safety systems protects atmospheric tanks in the case of crown fire with a vegetation height of 15 m.

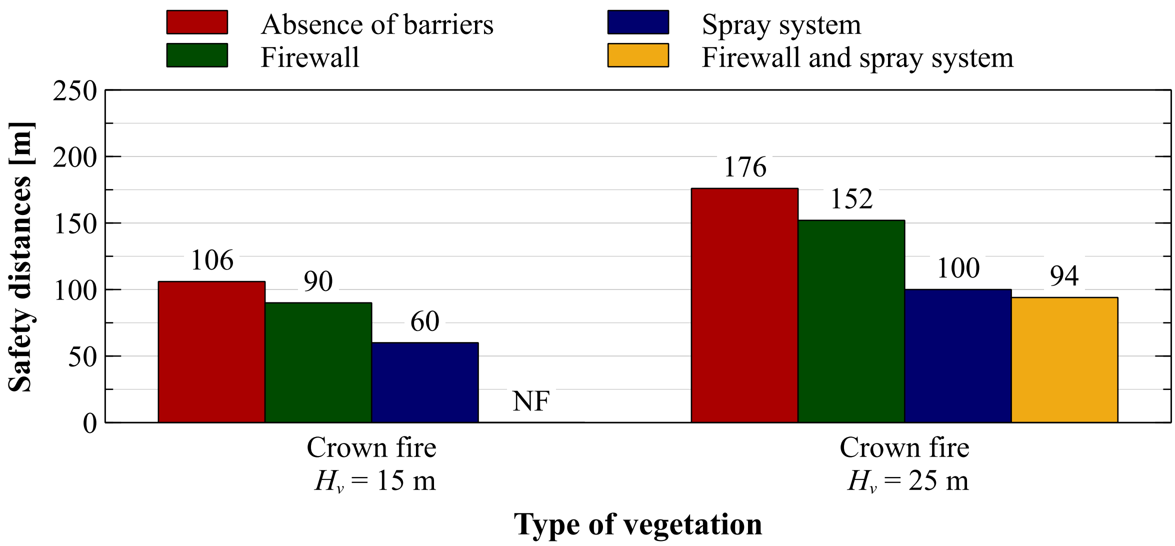

Figure 3.17. Specific safety distances for atmospheric tanks as a function of the type of vegetation and the presence of safety barriers considering a reference time of 5 min.

When 15 minutes are considered as the reference time, atmospheric tanks may be damaged by the fire regardless of the wildfire scenario considered if no safety measure is applied (Figure 3.18-a, red bars). Moreover, the figure highlights that firewalls and spray systems can protect the tanks even if used individually considering shrublands fire and forests with a tree height of 5 m. Indeed, safety distances obtained after their implementation are lower than the actual present in the layout (60 m). Despite this, the implementation of safety measures does not guarantee the integrity of the tanks even when used together if forests have heights of trees of 15 and 25 m. However, firewalls and spray systems reduce the safety distance by around 33 % and 50 % if applied separately, while a reduction of 60 % is obtained when applied simultaneously. As for pressurized tanks, the clearance area present in the layout ensures the tank integrity considering shrubland and forest with a vegetation height of 5 m, as can be derived looking at Figure 3.16. For the other types of vegetation, safety distances are reported in Figure 3.18-b. In such cases, the implementation of the firewall alone results to be ineffective. On the contrary, the spray system can ensure the integrity of the tank only when the tree height is of 15 m or lower. In addition, the safety measures considered do not reduce the safety distance sufficiently to make the tanks safe when dealing with tree heights of 25 m even when used together.

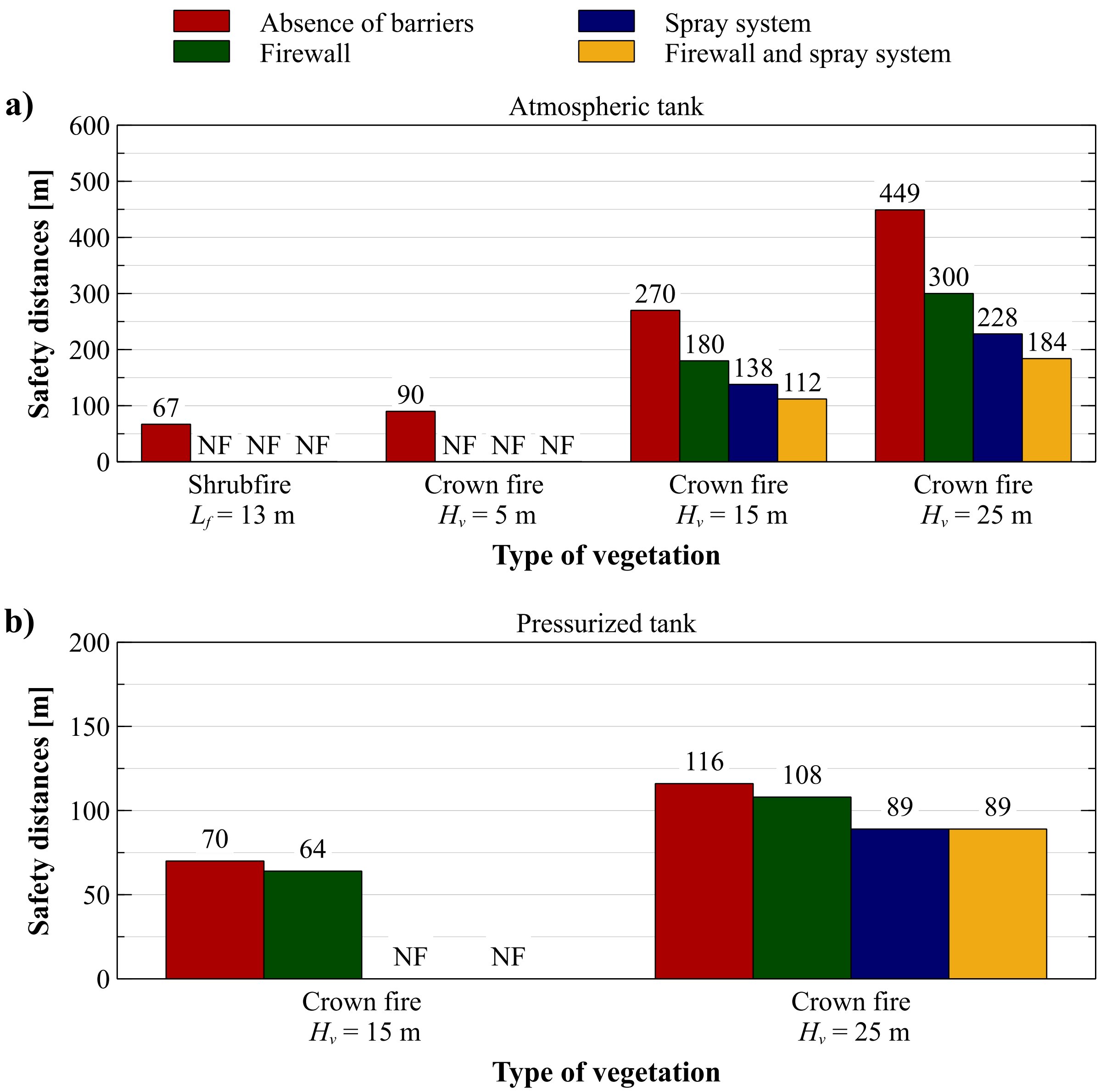

Figure 3.18. Specific safety distances as a function of the type of vegetation and the presence of safety barriers considering a reference time of 15 min for (a) atmospheric tanks and (b) pressurized tanks. Adapted from Ricci and co-workers [61].

Eventually, it is worth mentioning that the reduction of the safety distance obtained in the case of pressurized tanks is lower than the one related to atmospheric tanks. In addition, even if safety measures introduced in the layout do not ensure tank integrity, they result in an increase in the time to failure of tanks. Thus, the time available to emergency teams to protect the tanks increases, and consequently also the probability of a successful intervention.

3.5 Discussion

The methodology proposed in the present study provides a tool for the estimation of the safety distance between vegetation and storage tanks in industrial facilities, aiming at the prevention of tank failure and escalation leading to technological accident scenarios in the case of wildfires.

Each step of the methodology is developed based on simplifying assumptions that allow defining a straightforward approach, yet technically sound, to the assessment of safety distances. These assumptions may be interpreted as limitations to the field of application of the analysis and its results. From this perspective, Table 3.9 provides the main strengths and limitations identified for the developed methodology. Eventually, it is worth mentioning that each step of the methodology has a defined start and endpoint. Thus, as soon as new and reliable tools are available to perform one of the steps, these can be used to improve the methodology.

Table 3.9. Strengths and limitations for each step of the methodology developed for the calculation of safety distances.

Strengths	**Limitations**
Step 1: Characterization of the wildfire scenario	
The use of specialized software for fire spread modelling is not required. It allows a conservative assessment based on a straightforward estimation of wildfire characteristics.	No model exists to calculate the flame length for crown fires. The rules of thumb used are very conservative.
Step 2: Evaluation of the thermal radiation on targets	
The model used for the heat load calculation (i.e., the solid flame model) is consolidated and it is widely used even to assess the incident radiation in the case of wildfires [18,20,30].	The maximum value of the view factor between the fire and the target tank is applied.
Step 3: Calculation of the time to failure of targets	
The reduced number of input values simplifies the use of the methodology. Nomographs in Figure 3.8 and Figure 3.9 are easy to use and do not require any further calculation.	The application of the equations used for the time to failure calculation is limited to tank geometries used for their validation.
Step 4: Definition of safety distances	
It allows doing a site-specific assessment of safety distances based on emergency team response time.	No models exist to evaluate the duration of a wildfire event approaching the wildland-human interface.

It is also worth stressing that safety distances resulting from the present methodology are always conservative. Generic safety distances may be used as guidelines in defining layouts, providing adequate clearance area from the vegetation since the early design stages. Moreover, generic safety distance may be used as a screening tool in existing layouts before proceeding with the specific assessment. The specific assessment of safety distance allows evaluating the appropriateness of existing distances when considering a given layout. In addition, the application of the methodology to the assessment of tank-specific distances identifies the most vulnerable equipment items, driving decision-making on the adoption of safety systems for critical tanks (e.g. fireproofing, sprinklers, water curtains) and the improvement of emergency response plans in the case of wildfire (e.g., prioritizing the interventions of the firefighting teams towards the most critical tanks). Eventually, the effectiveness of safety barriers can be evaluated through the methodology. This allows identifying which safety measures are more effective to install or if they are sufficient to prevent the spread of wildfire inside the industrial plant when already installed.

Moreover, generic safety distances obtained in Section 3.4.1 are often higher than those proposed by technical standards and legislation. Table 3.10 and Table 3.11 reports a collection of standards and legislation which provide information on the separation distances between tanks and plant boundary for atmospheric and pressurized tanks respectively. It is worth mentioning that the reported technical standards and regulations prescribe safety distances to protect anything off-site from accidents that occur in the plant.

Table 3.10. Separation distances prescribed by guidelines and regulations for atmospheric tanks.

Standard/ Regulation	**Ref.**	**Prescribed distance [m]**	**Application**
Italian legislation	[66]	20	Minimum distance between storage tanks and plant boundary when the total storage capacity of flammable substances in the area is higher than 3500 m^3 (lower values are recommended for lower overall storage capacities).
Spanish legislation	[67]	30	Separation distance between plant boundary and tanks, regardless of the type.
Health and Safety Executive	[68]	15	Distance between tanks and plant boundary for tanks with volumes larger than 250 m^3.
National Fire Protection Association	[69]	105	It provides guidelines for the distance between atmospheric tanks and Third-Party properties. Distance depends on the characteristics of the tank. The distance reported corresponds to tanks with emergency relief venting (17 kPa) and no other protection system.

Table 3.11. Separation distances prescribed by guidelines and regulations for pressurized vessels.

Standard/ Regulation	Ref.	Prescribed distance [m]	Application
Italian legislation	[70]	40	Separation distances between tanks and plant boundary for LPG storage tanks featuring a volume higher than 300 m^3.
Greek legislation	[71]	30	Separation distances between tanks and plant boundary for pressurized vessels featuring a volume higher than 300 m^3.
Spanish legislation	[67]	30	Separation distance between plant boundary and tanks, regardless of the type.

It should be remarked that all the safety distances reported in Table 3.10 and Table 3.11 are lower than the generic safety distances obtained in the present study and reported in Figure 3.10, with differences as high as an order of magnitude. Even considering that the present methodology is conservative due to the assumptions at the base of each, the values obtained for generic safety distances raise some concern about the appropriateness of the clearance areas used in the current practice where severe wildfire scenarios are possible.

Eventually, it is worth mentioning that the present methodology is developed considering only one of the possible pathways through which a wildfire may affect industrial installation, which is thermal radiation. Clearly enough, the provision of safety distances, even if developed considering only thermal radiation, also allows avoiding the direct contact of the targets with flames. On the contrary, firebrands may travel long distances, thus affecting equipment items at distances higher than the safety distances obtained by the present methodology. Thus, further improvement of the methodology can be obtained by considering firebrands as an additional source of hazard for equipment items facing a wildfire front. Despite this, the outcomes of the present chapter represent a valuable tool to improve the safety of the tanks exposed to wildfire.

3.6 Conclusions

The present chapter aimed at providing a methodology to ensure the integrity of equipment items exposed to wildfire. This is achieved through the definition of adequate safety distances between vegetation and equipment items able to protect them and avoid the escalation of fire inside the plant. The proposed methodology is based on a technically sound approach and it allows for the definition of generic and specific safety distances in the absence and presence of safety barriers. The generic methodology for the calculation of safety distances is a valuable tool for a preliminary assessment of separation distances when detailed information on equipment items is not yet available. Thus, it is useful in the early design stages of the plant. Generic safety distances allow also a preliminary screening of equipment items possibly affected by the wildfire when existing layouts are evaluated.

The methodology for the calculation of tank-specific safety distances, instead, requires the knowledge of more detailed information on the equipment involved, such as the volume, and it allows a more precise and less conservative assessment of the safety distance required to protect the tank. In addition, the specific methodology allows defining a vulnerability ranking of the tanks, thus identifying the most vulnerable ones on which the installation of safety systems is a priority. From this perspective, this methodology considers also the inclusion of safety barriers (e.g., firewalls, spray systems), evaluating their effectiveness in avoiding fire spread within industrial sites. Eventually, the results of the methodology may be used for a better planning of the emergency response in the case of wildfires, directing the first intervention teams to the most vulnerable tanks. The application of the methodology to case studies highlights that safety distances currently used in industrial practice are not sufficient to ensure the integrity of tanks and prevent the escalation of fire inside the site. This result raises concern about the appropriateness of the safety distances prescribed by regulations and guidelines to avoid the failure of equipment items due to wildfire exposure. The methodology presented in the current chapter appears to be an important step toward the safety assessment of industrial sites possibly exposed to forest fires.

3.7 References

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Chapter 4: VULNERABILITY ASSESSMENT OF NATECH AND DOMINO SCENARIOS TRIGGERED BY WILDFIRES IN INDUSTRIAL PLANT

The risk caused by wildfires approaching the anthropic settlements poses an increasing concern, especially considering the Wildland-Urban Interface and, with respect to industrial installations, the Wildland-Industrial Interface. The large quantities of hazardous materials stored in industrial sites make them more vulnerable to the effects of wildfires. Moreover, safety distances prescribed by regulators and guidelines are often not sufficient to protect the facilities from the spread of wildfires resulting in domino effects and cascading events inside the plant. For these reasons, the present chapter aims at providing a methodology for the vulnerability assessment of industrial sites exposed to such natural events. The developed methodology allows for the calculation of primary Natech and related domino escalation scenarios, also considering the dynamic features of wildfires. The application of the methodology to a case study demonstrated that disregarding the dynamic behaviour of wildfire and related technological scenarios leads to a significant underestimation of the vulnerability. Eventually, results also demonstrated the importance of the intervention time on the overall vulnerability figures.

4.1 Introduction

Climate change and global warming are lengthening hot and dry seasons, causing larger and more frequent wildfires [1–6], as reported in detail in Chapter 1. The concern about the wildfire issue raises when considering fire fronts approaching anthropic settlements, as they become a potential threat to human health, civil structures, and industrial facilities [7]. In addition, the study of WII fires becomes even more important considering the presence of large quantities of hazardous materials. In such cases, fire events (including wildfire) may lead to catastrophic events and trigger domino escalations [8–17]. To avoid the spread of wildfire inside industrial installations, a technically sound approach for the calculation of safety distances between wild vegetation and equipment items was proposed in Chapter 3. In addition, the lack of harmonized and appropriate safety distances in legislation and technical standards has been highlighted. This suggests that the safety of industrial sites exposed to wildfire is not guaranteed, especially in the case of existing plants. From this perspective, the present chapter aims at answering the following research question:

In the case of wildfires impacting industrial sites, how to assess the vulnerability of the plant?

Recently, Khakzad and collaborators introduced the problem of wildfire risk assessment for industrial installations [18,19]. The study addressed specific critical aspects of the risk, such as the revenue loss due to operational shutdown in the case of wildfires.

Even if a general framework for the quantitative risk assessment of Natech accidents exists in the literature [20], this was applied to date mostly to earthquakes, floods, and lightning [21–27]. These approaches generate a set of possible mutually exclusive combinations, without taking into account the time sequence of the scenarios. Hence, the dynamic behaviour of wildfire events and related industrial accidents would be neglected by applying such methodologies, potentially leading to flawed results considering wildfires.

For these reasons, a dynamic methodology for the vulnerability assessment of industrial sites exposed to wildfires is presented in the present chapter which considers the time sequence of the events. The approach considers both primary Natech accidents and related domino escalation scenarios, and it is able to capture the synergistic effect of multiple simultaneous fires. The vulnerability of industrial sites is evaluated regardless of the wildfire frequency affecting them. However, the risk of industrial sites exposed to wildfires can be obtained from the methodology developed in the present study once the wildfire frequency is known.

The assessment of wildfire frequency is a case-specific task requiring in-depth evaluations and multidisciplinary approaches that are beyond the scope of the present study. Some methodologies are available in the literature for the estimation of the likelihood of wildfires in specific countries [73–79]. The interested reader can refer to the technical literature for wildfire frequency evaluation.

The methodology is presented in Section 4.2. A case study is defined in Section 4.3 and results from the application of the methodology are reported in Section 4.4. The same section also reports a comparison between the methodology developed in the present study and those existing in the literature for Natech Quantitative Risk Assessment. Moreover, the influence of the intervention time of emergency teams on the vulnerability is evaluated. Section 4.5 addresses the discussion of the assumption at the base of the methodology and of the related results. Eventually, Section 4.6 summarizes some conclusions.

4.2 Methodology

The methodology proposed for the vulnerability assessment of industrial sites with respect to primary Natech and the related domino escalation scenarios triggered by wildfire events is outlined in Figure 4.1. The methodology is based on an innovative dynamic procedure that accounts for the specificities of wildfire events and related cascading Natech accidents.

The methodology can be summarized in three main parts as reported in Figure 4.1:

- Part 1: Characterization of the wildfire.
- Part 2: Dynamic assessment of primary Natech and domino escalation scenarios. This part of the methodology is developed to account for the specificities of wildfire-induced accidents.
- Part 3: Vulnerability calculation, aimed at the calculation of consequences and vulnerability indices.

A detailed description of each step is provided in the following sections, highlighting the main features conceived to catch the specificities of Natech accidents driven by wildfires. The results of the methodology allow for the calculation of the fatalities distribution and identify the most critical areas of the site. Moreover, the risk can also be evaluated through the methodology once the frequency of the wildfire events is known.

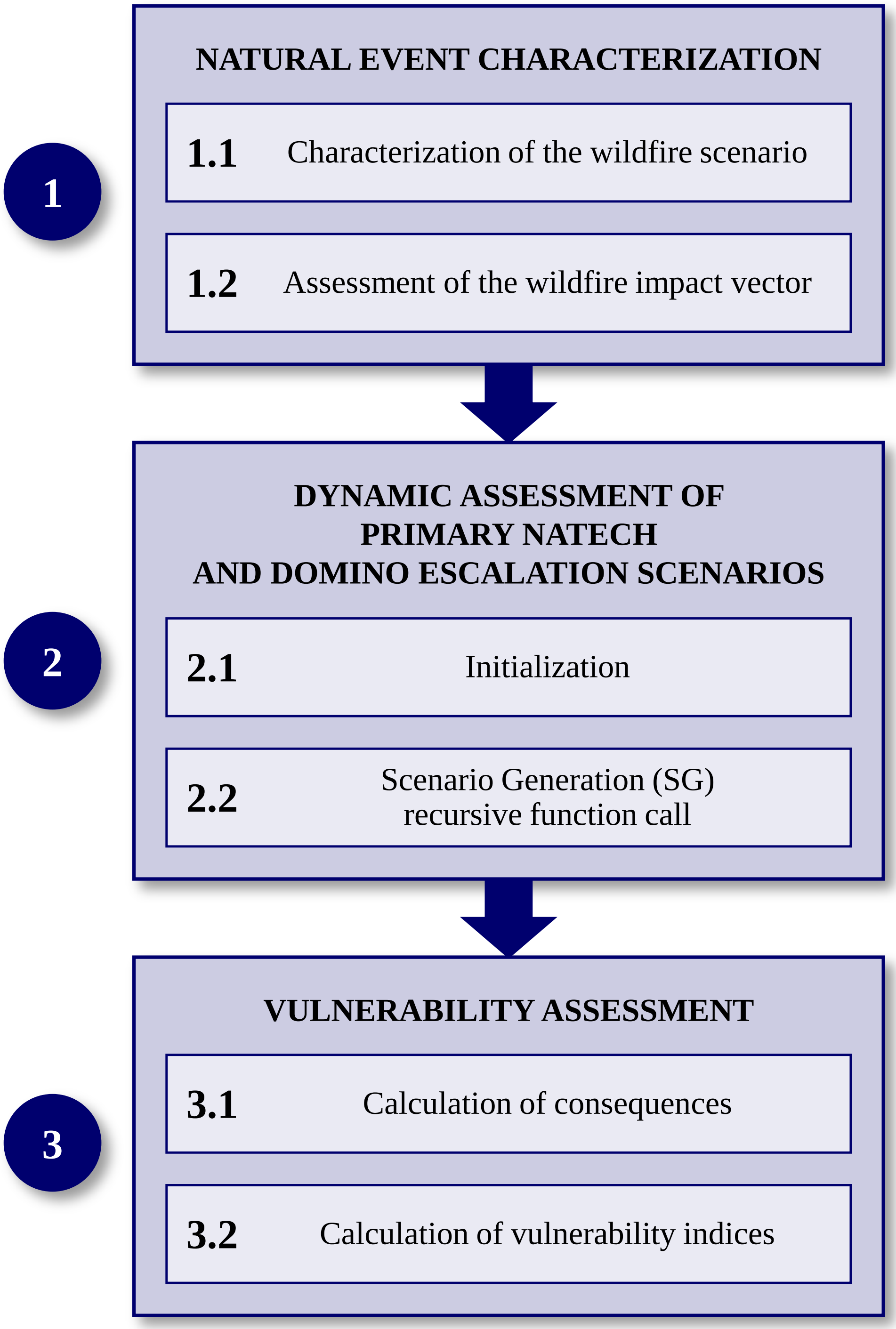

Figure 4.1. Flowchart of the methodology developed for the vulnerability assessment of primary Natech and related domino escalation scenarios triggered by wildfires.

4.2.1 Natural event characterization

The natural event characterization consists of two steps: the characterization of the wildfire scenario and the assessment of its impact on targets, as shown in Figure 4.1.

4.2.1.1 Characterization of the wildfire scenario

Several methods were developed in the literature for forest fire vulnerability, hazard and risk evaluation [28]. Some methods derive from the application of statistical and data-mining models [29–32]. Some others leverage the application of machine learning models [33–35] or use ensemble models [36,37]. Moreover, software such as PROMETHEUS [38], SPARK [39], and FARSITE [40] are available to model wildfire behaviour and allow for the evaluation of fire propagation throughout vast areas, both in terms of spreading rate and intensity. As introduced in Section 3.2.1, these methodologies provide results extremely specific to the wildfire event under analysis. Indeed, they require the evaluation of several factors characterizing the burning fuel, the weather condition and the morphological aspects of the territory. Moreover, these models are developed to simulate wildfire behaviour within vast vegetation areas. Thus, they do not account for local variations in the fuel distribution and wind profile which may affect a wildfire approaching the edge of the vegetation [41]. This aspect is particularly relevant when considering wildfires affecting the wildland industrial interface [42]. For these reasons, the application of these methodologies is difficult in the context of the QRA of industrial installations exposed to wildfires.

Therefore, the use of the simplified methodology proposed in Chapter 3 of the present work is suggested to perform a conservative evaluation of the reference wildfire scenario magnitude. The main features of the methodology are summarised in the following. The methodology is based on the solid flame model approach. Thus, the fire front is modelled as a solid surface with a fixed shape, size, and emissive power E_{wf}. A conservative value of 118 kW/m^2 is assumed for this last parameter according to the assumptions discussed in Section 3.2.1 and applied by several previous studies [43–46]. As shown in Figure 4.2, the wildfire front is schematized as a rectangular surface of height equal to the flame length L_f and length equal to the fire-front width W_f, inclined to the ground by a tilt angle θ.

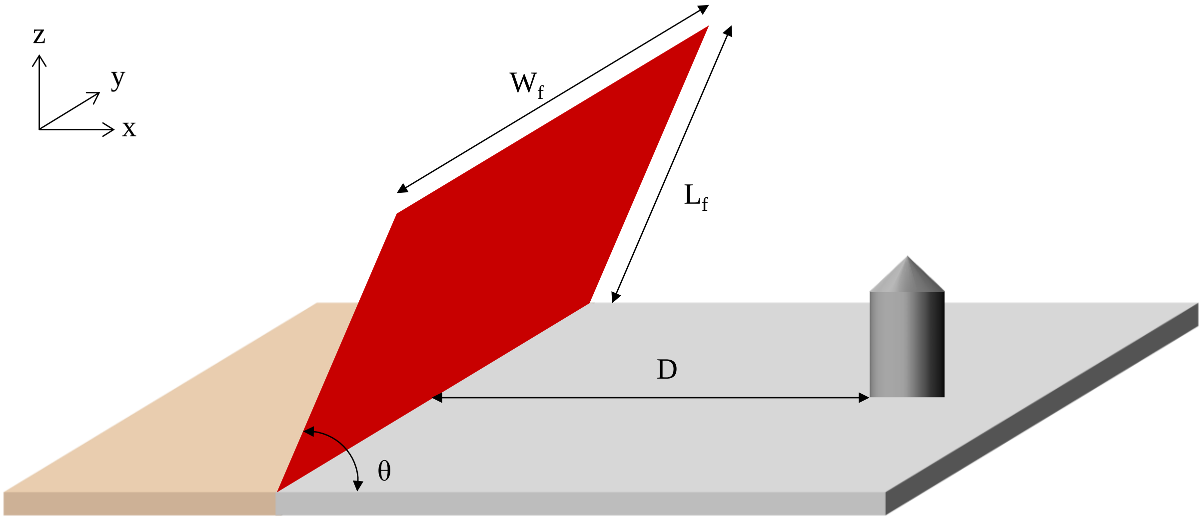

Figure 4.2. Representation of the flame shape and size. L_f: flame length, W_f: fire-front width, D: distance between wildfire and target, θ: flame tilt angle.

The fire-front width W_f is conservatively assumed as infinite and the tilt angle θ is the one that maximizes the view factor (and therefore the incident radiation on targets). Eventually, the flame length L_f is defined according to the type of vegetation growing in the proximity of the plant boundary, and it can be calculated using Eq. 4.1, where H_v is the height of the trees when considering forests.

$$L_f = \begin{cases} 7.5 & \text{Grassland fire (GF)} \\ 13 & \text{Shrubland fire (SF)} \\ 3.5 \cdot H_v & \text{Crown fire (CF)} \end{cases} \qquad \text{Eq. 4.1}$$

4.2.1.2 Assessment of wildfire impact vector on industrial installation

The second step requires the assessment of the wildfire impact on targets (Step 1.2 in Figure 4.1). As argued in Chapter 3, wildfire impact on industrial installations mainly occurs through thermal radiation, as flame engulfment is typically avoided due to the presence of a clearance area [47–51]. Thus, for the generic *i-th* target, the impact vector assessment reduces to the calculation of the incident radiation $IR_{wf \to i}$ according to Eq. 4.2:

$$IR_{wf \to i} = E_{wf} \cdot F_{wf \to i} \cdot \tau_a \qquad \text{Eq. 4.2}$$

where E_{wf} is the wildfire emissive power (W/m^2), $F_{wf \to i}$ is the view factor between the wildfire and the i-th tank (dimensionless), and τ_a is the atmospheric transmissivity (dimensionless). The latter parameter is conservatively assumed equal to 1.

According to the flame shape considered in the present study (see Figure 4.2), the view factor $F_{wf \to i}$ can be calculated following the model proposed by Mudan [52].

4.2.2 Dynamic assessment of primary Natech and Domino escalation events

The core of the methodology proposed in the present study is related to the dynamic assessment of primary Natech and Domino escalation events (Part 2 in Figure 4.1). The aim is to define the event tree describing the dynamic chain of events. The obtained event tree allows for considering all possible scenarios and calculating the related occurrence probability. This is done through an algorithm consisting of two steps:

- Initialization
- Scenario Generation (SG) recursive function call

The flowcharts of the initialization step and the SG recursive function are illustrated in Figure 4.3.

Initialization

- Define the list of targets ***T*** to be included in the analysis
- Set all the elements of the status vector ***S*** to "*vulnerable*"
- Set all the elements of the thermal dose vector ***TD*** to 0
- Set all the elements of the impact vector ***I*** to 0
- Set the current time *t* to 0
- Set the generic probability *P* to 1

*# Note: **T**, **S**, **TD** and **I** have a number of elements equal to the number of targets considered*

SG recursive function

```
SG(S, TD, t, P)
  |   for each target in "vulnerable" status, calculate the impact vector I(S, t)
  |   # Note: I(S, t) consider the impact of the wildfire on targets over the time
  |   for each target in "vulnerable" status, calculate the time to failure ttf (I, S, TD, t)
  |   identify the most vulnerable target MVT as the one with the lowest ttf
  |   calculate the failure probability P_fail (ttf) for MVT
  |   split the current branch creating a lower and an upper sub-branches
  |   if S contains only 1 element in "vulnerable" status
  |       |   assign the value P · (1- P_fail (ttf)) to the lower sub-branch
  |       |   assign the value P · P_fail (ttf) to the upper sub-branch
  |   else
  |       |   update the thermal dose vector TD(I, S, TD, t, ttf) for domino escalation
  |       |   # Note: development of the lower sub-branch
  |       |   in the status vector S, set to "protected" the element corresponding to MVT
  |       |   call SG(S, TD, ttf, P · (1- P_fail (ttf)))
  |       |   # Note: development of the upper sub-branch
  |       |   evaluate the escalation potential of the outcome resulting from the MVT
  |       |   if escalation is possible
  |       |       |   in the status vector S, set to "on fire" the element corresponding to MVT
  |       |       |   call SG(S, TD, ttf, P · P_fail (ttf))
  |       |   else
  |       |       |   in the status vector S, set to "failed" the element corresponding to MVT
  |       |       |   call SG(S, TD, ttf, P · P_fail (ttf))
  |       |   end
  |   end
end
```

Figure 4.3. Flowcharts of the initialization step and the Scenario Generation (SG) recursive function.

The initialization step begins with the identification of all the *T* targets (e.g. pressurized and atmospheric tanks) to be included in the analysis. Then, the status vector ***S*** is defined. Each element of ***S*** corresponds to one element of *T* and it can assume 4 values (or states):

- *Vulnerable*: the target is intact and, when exposed to fire, may either fail or be protected by emergency teams.
- *Protected*: emergency teams were able to secure the target before failure. The "*protected*" status is permanent. Hence, a protected target on a given event tree branch cannot change its state along the connected sub-branches.
- *Failed*: the target fails. This status is associated with those targets whose outcome is not able to trigger a domino escalation scenario (i.e., they do not influence the impact vector *I*).
- *On fire*: the target fails. It is attributed to those targets whose outcome has the potential to trigger domino escalation scenarios (i.e., modifying the impact vector *I*).

The distinction between the "*failed*" and "*on fire*" states is better clarified in Section 4.2.2.1. In the initialization step, each element of the vector ***S*** is set to "*vulnerable*", while elements in the thermal dose vector ***TD*** are set to 0. Eventually, the current time *t* and the generic probability *p* are set to 0 and 1 respectively.

Once all the required variables are initialized, the Scenario Generation (*SG*) function is called. This is a recursive function that generates a quantified event tree. To do so, *SG* calls itself repeatedly until the space of possible scenarios is completely explored and their occurrence probability is quantified. A set of subfunctions is present in *SG*, which are described in detail in the next sections. Here, the general workflow of the *SG* function is illustrated.

Given a generic node in the event tree, the *SG* function calculates the impact vector by calling the subfunction *I(S,t)* on all tanks in "*vulnerable*" status. The impact vector calculation depends on the status of all targets and on the current time *t* (see Section 4.2.2.1). Then, the time to failure *ttf* of all "*vulnerable*" targets is obtained by calling the function *ttf(I, S, TD, t)* (see Section 4.2.2.2). The tank with the lowest *ttf* is identified as the most vulnerable tank *MVT* and its failure probability is calculated based on the probit function approach illustrated in Section 4.2.2.4. At this point, the current event tree branch is split into two sub-branches and two cases are possible depending on the number of "*vulnerable*" tanks. If the *MVT* is the only one in "*vulnerable*" status, the *SG* function call ends by returning the occurrence probability for the lower (the *MVT* is successfully protected by the emergency teams) and the upper sub-branches (the *MVT* fails). Otherwise (more than one target is in "*vulnerable*" status), the ***TD*** vector is updated on the base of the *ttf* corresponding to the *MVT* (see Section 4.2.2.3) and the "recursive section" of the *SG* function is activated. First, the ***S*** element corresponding to the *MVT* is set to "*protected*" and a new instance of the function is called with ***S***, ***TD***, *ttf* and $P \cdot (1 - P_{fail}(ttf))$ as inputs. In this way the algorithm moves along the lower sub-brunch, developing the event tree until no "*vulnerable*" target is left. Then, the upper sub-brunch is considered. The same ***S*** element is changed into the "*failed*" or "*on fire*" state depending on the type of outcome, and the *SG* function is called with ***S***, ***TD***, *ttf* and $P \cdot P_{fail}(ttf)$ as inputs. Again, the algorithm will repeatedly call *SG* until all possible scenarios are explored and quantified.

In the following sections, the main steps and subfunctions composing the *SG* function are described in detail.

4.2.2.1 Impact vector calculation

The impact vector represents the physical effect that affects a target and it can cause its failure. Thus, its calculation consists of the quantification of the contribution to the escalation that reaches each target considered in the analysis. This is the result of the combination of all outcomes of the accidental event having the potential to induce equipment failure. In the present framework, two events are considered: the presence of a wildfire at the plant boundary and the failure of one or more targets. As discussed in Section 4.2.1.2, the only outcome of interest related to the wildfire is the thermal radiation generated by the firefront. The identification of the outcomes of interest resulting from target failure requires some further consideration. Indeed, different typologies of scenarios may take place (e.g., pool fires, fireballs, toxic dispersion, missiles) depending on the type of loss of containment, the features of the failed targets and the hazardous properties of the released substance [53–56]. However, only a limited number of such events have the potential to trigger escalation and an even smaller subset can be deemed credible in a wildfire-induced Natech scenario.

According to the literature on domino effects [10,57,58], catastrophic failure is the most credible loss of containment type for items exposed to an external fire. In addition, the presence of flames due to the wildfire (or other fires resulting from one or more failed tanks) increases considerably the likelihood of ignition in case of flammable substance releases. Indeed, the three accidental scenarios triggered by wildfires analysed in Section 2.6 resulted in a scenario which requires an ignition source. These considerations limit the outcomes to be accounted for in the escalation assessment to pool fires resulting from the immediate ignition of a flammable substance released after the catastrophic failure of atmospheric tanks. The fire scenarios resulting from the catastrophic failure of pressure tanks (i.e., fireball and flash fire) are excluded from the outcomes of interest for escalation assessment. Indeed, the short duration of these scenarios prevents the possibility of escalation according to Cozzani and co-workers [10]. Nevertheless, such scenarios are considered in the vulnerability calculation steps (Part 3 in Figure 4.1).

In light of the above, the quantification of the impact vector (namely the incident radiation) affecting each tank at a given time t can be obtained by combining two contributions. The first one is the thermal radiation from the wildfire, which is calculated according to the procedure reported in Section 4.2.1.2. The second one, instead, is the thermal radiation from the pool fires generated by the atmospheric tanks that have failed, which is evaluated through well-established literature models [53–55].

It should be noted that the duration of industrial fires is typically higher than the time to failure *ttf* of most common target tanks. Thus, they are usually considered stationary events in QRA [53–56]. The same assumption is not credible for wildfires burning at the edge of vegetation. Indeed, experienced firefighters suggest that 15 min is a credible time representing the maximum duration of wildfires at the wildland industrial interface, as discussed in Section 3.2.4. The same value is adopted in the present methodology. In addition, a constant value of thermal radiation as calculated in Section 4.2.1.2 is considered for the entire duration of the wildfire. Thus, when calculating the impact vector $\boldsymbol{I}(\boldsymbol{S}, t)$, the *i-th* element of $\boldsymbol{I}$ is defined as a step function in the form of Eq. 4.3:

$$\begin{cases} I_i = IR_{wf\to i} + \sum_{j=1}^{n} \delta_j \cdot IR_{j\to i} & \text{t} < 15 \text{ min} \\ I_i = \sum_{j=1}^{n} \delta_j \cdot IR_{j\to i} & \text{t} \geq 15 \text{ min} \end{cases} \qquad \text{Eq. 4.3}$$

where $IR_{wf\to i}$ is the thermal radiation on the *i-th* target from the wildfire, $IR_{j\to i}$ is the incident radiation on the *i-th* target from the *j-th* item, *n* is the total number of tanks considered in the analysis, and δ_j is a parameter set to 1 if the status of the *j-th* item is "*on fire*", 0 otherwise. Noteworthy, the calculation of the impact vector is performed only for tanks in "*vulnerable*" status.

It should be noted that the approach developed in the present work aims at providing a methodology to account for the dynamic behaviour associated with wildfire and fire-induced escalation scenarios. Thus, even if other possible escalation vectors such as fragment projection following explosions are possible [59–65], their assessment is out of the scope of this study, being heat radiation the driver of escalation considered. Despite this, the methodology could be modified to consider missiles or other impact vectors as escalation factors.

4.2.2.2 Time to failure calculation

The calculation of the time to failure *ttf* for a generic *i-th* target tank is carried out following the method proposed by Zhou et al. [66]. It allows for capturing the dynamic and synergistic effect of multiple fires starting and ending at different times. The method is based on the concepts of thermal dose *TD* and critical thermal dose TD_C, which were first introduced by Ding et al. [67]. The thermal dose received by the *i-th* target TD_i is defined as the integral over time of the incident radiation received by the target as shown in Eq. 4.4:

$$TD_i = \int_{t_1}^{t_2} I_i^{\alpha} \cdot d\tau \qquad \text{Eq. 4.4}$$

where I_i is the thermal radiation received by the target and calculated according to Eq. 4.3, τ is time, t_1 and t_2 are integration extremes, and α is a coefficient which takes into account the different weights to be attributed to the thermal radiation and the time.

The critical thermal dose TD_C, instead, is the thermal dose required to induce the failure of the tank. Considering the simplified correlations for the calculation of *ttf* provided by Landucci et al. [12], the coefficient α can be easily derived. Hence. α is equal to 1.128 and 0.947 respectively for atmospheric tanks and pressurized vessels. From the same correlations, the critical thermal dose TD_C can be calculated for the same type of targets as a function of the volume *V* (m^3) using Eq. 4.5 and Eq. 4.6 respectively:

$$TD_{C,atm} = \exp\left(-2.667 \cdot 10^{-5} \cdot V + 9.877\right) \qquad \text{Eq. 4.5}$$

$$TD_{C,press} = \exp\left(8.835 \cdot V^{0.032}\right) \qquad \text{Eq. 4.6}$$

When the *SG* function calls *ttf(**I**, **S**, **TD**, t)*, the time to failure for an ***i-th*** target in "*vulnerable*" status is calculated as the time at which the thermal dose TD_i equals the critical one $TD_{C,i}$. In other words, the time to failure of the *i-th* target ttf_i is the value that satisfies Eq. 4.7:

$$ttf_i = t + \frac{TD_{C,i} - TD_i}{\frac{1}{ttf_i - t} \cdot \int_t^{ttf_i} I_i^{\alpha} \cdot d\tau} \qquad \text{Eq. 4.7}$$

where TD_i is the thermal dose received by the *i-th* target up to time *t*.

The denominator at the second term of Eq. 4.7 represents the average thermal radiation received by the *i-th* target in the time interval between *t* and its ttf_i. This allows accounting for the variation in the thermal radiation that occurs when the wildfire ends. Noteworthy, the ttf_i calculated according to Eq. 4.7 refers to the time elapsed between the moment in which the wildfire approaches the plant boundary and the failure of the tank. Eventually, the tank with the lowest time to failure *ttf* is identified as the most vulnerable tank *MTV*.

4.2.2.3 Thermal dose update

The ttf_i corresponding to the *MVT* is used in Eq. 4.8 to update each element of the thermal dose ***TD*** vector corresponding to tanks in "*vulnerable*" status.

$$TD_{i,updated} = TD_{i,old} + \int_t^{ttf_i} I_i^{\alpha} \cdot d\tau \qquad \text{Eq. 4.8}$$

4.2.2.4 Calculation of failure probability

Following the approach proposed in several studies available in the literature for the assessment of the domino effect [10,12,66,68], the calculation of the damage probability is carried out using a probit model. The model is based on the calculation of the probit variable *Y* as reported in Eq. 4.9, where *A* and *B* are the probit coefficients and *X* represents the generic vector impacting the target:

$$Y = A + B \cdot \ln(X) \qquad \text{Eq. 4.9}$$

In the specific case of fire-induced domino effect assessment, Landucci et al. [12] proposed to estimate the probit value based on the time to failure (i.e., by posing $X = ttf$ in Eq. 4.9) and to derive the parameters A and B by comparing the *ttf* with the characteristic times required for emergency teams intervention. This depends on the site-specific emergency response plan and, if this information is not available to the analyst, it can be estimated using values reported in the literature. According to the same authors [12], there is typically a 10 % probability that a successful intervention occurs within 5 min from the beginning of the fire, while this value increases up to 90 % at 20 min. Based on these considerations, and assuming a unitary efficiency of the intervention (i.e., if the emergency teams intervene, the failure of the target is avoided), the failure probability of an equipment item P_{fail} can be calculated as the complement to the unity of the emergency teams intervention probability. Thus, coefficients A and B can be derived according to the following equations:

$$A = \frac{Y_2 \cdot \ln(t_1) - Y_1 \cdot \ln(t_2)}{\ln(t_1) - \ln(t_2)} \qquad \text{Eq. 4.10}$$

$$B = \frac{Y_1 - Y_2}{\ln(t_1) - \ln(t_2)} \qquad \text{Eq. 4.11}$$

where Y_1 and Y_2 are the probit values related to the failure probability associated with the time t_1 and t_2 respectively. The probit variables Y_1 and Y_2 can be evaluated knowing the failure probability ($P_{fail,1}$ = 0.9 and $P_{fail,2}$ = 0.1) according to the mathematical models available in the literature [53,54,56], resulting equal to 6.282 and 3.718 respectively. Then, coefficients A and B for the estimation of the probit variable can be obtained by associating the time values to the failure probability defined above (t_1 = 5 min and t_2 = 20 min). Table 4.1 reports the coefficients A and B to be used in Eq. 4.9 for the calculation of the probit variable.

It is important to remark that the reference intervention time values of 5 and 20 min were proposed by Landucci et al. [12] considering the case of a tank exposed to a single fire in a conventional accident. During wildfires and wildfire-induced accidents, several factors such as the shortage of firefighting materials or the harsh conditions caused by the smoke may hamper the emergency response team intervention, delaying the intervention time. Even if a detailed analysis of all possible interactions between wildfire and emergency teams intervention is beyond the scope of the present study, ignoring this issue might lead to an underestimation of the vulnerability. For this reason, two additional pairs of reference values for the intervention time are considered in the present work. These are derived by applying a multiplying factor (γ) of 1.5 and 2 to the reference values proposed by Landucci et al. [12]. The probit coefficients obtained considering the modified intervention time are reported in Table 4.1.

Table 4.1. Parameters for the calculation of the probit variable according to Eq. 4.9 for the evaluation of the failure probability of tanks.

Parameters	**γ = 1**	**γ = 1.5**	**γ = 2**
Upper reference value for the intervention time [min]	5	7.5	10
Lower reference value for the intervention time [min]	20	30	40
Coefficient A in Eq. 4.9	9.257	10.007	10.539
Coefficient B in Eq. 4.9	-1.849	-1.849	-1.849

Once evaluated the probit variable, the failure probability $P_{fail}(Y)$ can be evaluated according to Eq. 4.12 as reported in the technical literature [53,54,56]. Clearly, the probability of the branch in which the equipment item does not fail can be calculated as 1-$P_{fail}(Y)$.

$$P_{fail} = 0.5 \cdot \left[1 + \text{erf}\left(\frac{Y-5}{\sqrt{2}} \right) \right] \quad \text{Eq. 4.12}$$

Noteworthy, the emergency intervention times defined for the present analysis have a purely illustrative purpose. It is necessary to develop technically sound approaches for the evaluation of the emergency response to obtain more reliable time intervals and results.

4.2.3 Vulnerability assessment

Once all possible scenarios are generated through the *SG* function (see Section 4.2.2), the procedure continues with the consequence assessment (Step 3.1 in Figure 4.1). It is worth mentioning that the *SG* function provides the probability of occurrence and an ***S*** vector containing the status of each target for each generated scenario.

Conventional models for consequence assessment cannot be applied directly to the case of Natech and domino scenarios, as they assume single-point source scenarios [53–55]. Natech and domino scenarios are instead characterized by multiple and heterogeneous outcomes, and their consequences are evaluated following a standardized simplified approach. The approach normalizes the sum of the death probabilities related to each outcome taking part in the combined scenario [20–24,26,69], considering an upper limit of 1. Thus, the consequences in a generic position due to the *q-th* combined scenario C_q can be calculated according to Eq. 4.13:

$$C_q = \min\left(\sum_{i=1}^{S_{tot}} \delta_i \cdot C_i , 1 \right) \quad \text{Eq. 4.13}$$

Where C_i is the death probability associated with the *i-th* equipment item, and δ_i assumes a value of 1 if the ***i-th*** element of the ***S*** vector is "*failed*" or "*on fire*", 0 otherwise. The death probability related to each target C_i can be estimated by applying the human vulnerability model to the physical effects, such as probit models. The physical effects can be carried out according to models available in the literature for consequence analysis, based on the loss of containment and the hazardous properties of the released substances [53,54,56].

Then, the vulnerability of the industrial site to primary Natech and domino escalation scenarios triggered by wildfire can be evaluated (Step 3.2 in Figure 4.1). The extension of zones potentially affected by the wildfire events may be based on the calculation of "lethality maps". Lethality maps are contour plots in which curves related to a given death probability are reported. These maps allow the identification of the areas of the site most affected by technological scenarios triggered by wildfire events.

If the expected frequency or time of return of a wildfire at the site of interest is known, the present methodology may be used as well to evaluate risk figures for the industrial site, such as the Local-Specific Individual Risk (LSIR) and the Societal Risk [53,54,56]. In addition, other indices can be computed to support a more concise presentation of societal vulnerability figures [24,26,69–72]: the Potential Life Loss (PLL) and the Expectation Value (EV). Equations for the calculation of the indices are reported in Eq. 4.14 and Eq. 4.15 respectively.

$$PLL = \sum_N f\left(N\right) \cdot N \qquad \text{Eq. 4.14}$$

$$EV = \sum_N f\left(N\right) \cdot N^a \quad \text{with } a > 1 \qquad \text{Eq. 4.15}$$

where f is the simple frequency of the scenario related to N fatalities and N is the number of fatalities. It is worth mentioning that the exponent a in the calculation of the Expectation Value allows associating a more severe social perception to scenarios causing a high number of fatalities N. A value of 2 is assigned to the exponent a in the present study, consistently with other studies on the QRA of Natech accidents and domino effects [24,26,69].

4.3 Case Study

A simplified case study was defined to demonstrate the applicability of the proposed methodology. The layout considered for the case study is shown in Figure 4.4.

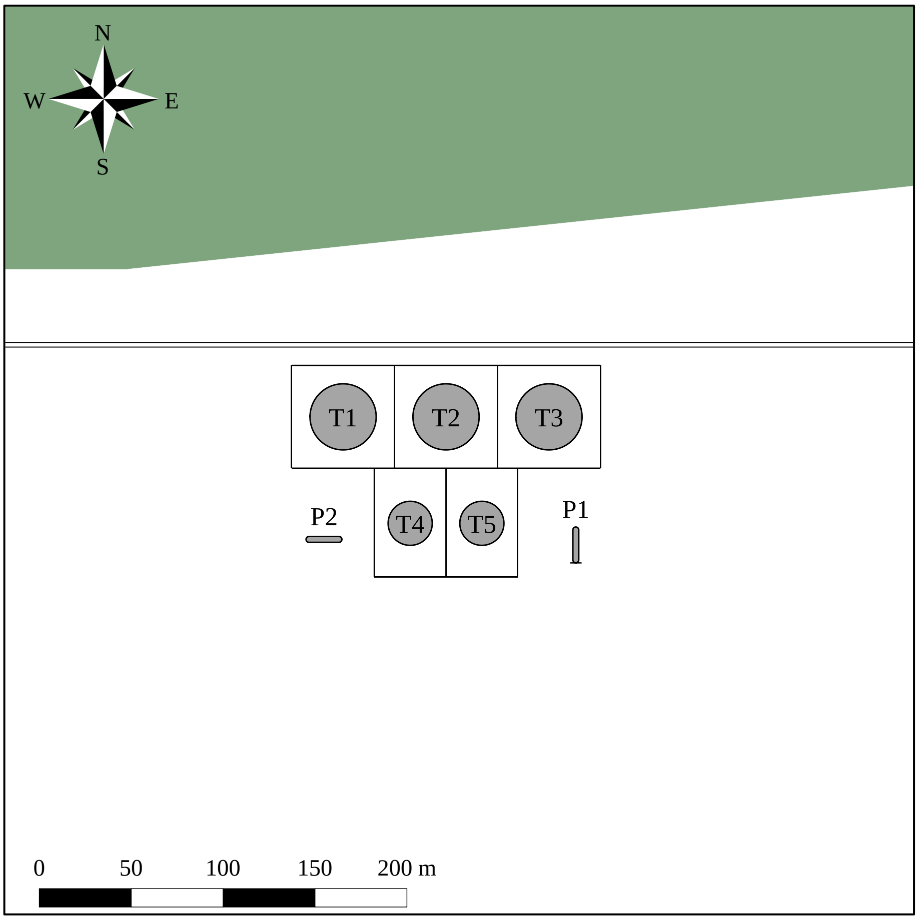

Figure 4.4. Layout considered in the case study. The green area in the figure represents the forest.

The case study consists of a storage area where 5 atmospheric tanks (T1-T5 in Figure 4.4) and 2 horizontal pressurized vessels (P1-P2 in Figure 4.4) are present. A forest faces the northern border of the storage site (green area in Figure 4.4). The average height of vegetation H_v is assumed to be equal to 10 m. The main features of equipment items are reported in Table 4.2. Distances between the forest and each tank are reported in Table 4.3, as well as the separation distances (edge-to-edge) among tanks.

Table 4.2. Description of equipment items considered in the case study.

Tank	T1-T3	T4-T5	P1	P2
Type	Atmospheric tank	Atmospheric tank	Pressurized vessel	Pressurized vessel
Nominal volume [m^3]	9161	4069	150	150
Diameter [m]	36	24	3.2	3.2
Length [a]/Height [b] [m]	9	9	19.4	19.4
Filling level	75%	75%	90%	90%
Substance	Petroleum crude	Gasoline	Ammonia	Propane
Physical state	Liquid	Liquid	Liquefied gas	Liquefied gas
Operating pressure [bar]	1.0	1.0	8.5	8.5
Inventory [ton]	6524	2289	81	74

[a] Horizontal vessels (P1-P2)

[b] Vertical vessels (T1-T5)

Table 4.3. Distances (in meters) of tank T_i from wildfire (WF) and tank T_j. Distances are calculated from the tank edge.

$T_i \backslash T_j$	WF	T1	T2	T3	T4	T5	P1	P2
T1	75	-	*(20)*	*(76)*	*(38.5)*	*(65.3)*	*(126)*	*(40.7)*
T2	82	20	-	*(20)*	*(31.2)*	*(31.2)*	*(80.6)*	*(64.7)*
T3	89	76	20	-	*(65.2)*	*(38.5)*	*(52.5)*	*(110.5)*
T4	143	38.5	31.2	65.2	-	*(15)*	*(78.6)*	*(26.8)*
T5	147	65.3	31.2	38.5	15	-	*(40)*	*(65.8)*
P1	168	126	80.6	52.5	78.6	40	-	*(129.1)*
P2	158	40.6	64.7	110.5	26.8	65.8	129.1	-

The appropriateness of the present dynamic approach is evaluated against methodologies available in the literature for the evaluation of Natech accidents and domino effects [20–23,26] when considering wildfires-induced accidents. For this reason, two cases were defined:

- **Case 1** (Conventional methodology for Natech assessment). The assessment is performed according to the methodology proposed in the literature by Cozzani and co-workers [10,20,26]. Specifically, the second level of domino escalation is applied for the evaluation of cascading events, being the impact vector from wildfires comparable to an industrial fire (e.g., pool fire, jet fire, etc.).
- **Case 2** (Present methodology). The assessment is performed according to the dynamic methodology developed in the present study.

In both cases, 5 and 20 min are assumed as lower and upper values for the intervention time (i.e., $\gamma = 1$, in Table 4.1). To explore the effect of delayed emergency response on the vulnerability, two additional cases are defined:

- **Case 3** (Present methodology, $\gamma = 1.5$). The evaluation is performed according to the dynamic methodology developed in the present study considering a delay in the emergency intervention. A delay factor γ equal to 1.5 is assumed to evaluate the probit variable (see Section 4.2.2.4 and Table 4.1).
- **Case 4** (Present methodology, $\gamma = 2$). The evaluation is performed according to the dynamic methodology developed in the present study considering a delay in the emergency intervention. A delay factor γ equal to 2 is assumed to evaluate the probit variable (see Section 4.2.2.4 and Table 4.1).

The plant considered as a case study is assumed located in the Willamette Valley (Oregon, USA) since the time of return of a wildfire is available for the site. The predicted Mean Fire Interval in the area is around 6 years according to Guyette et al. [73]. Thus, a wildfire frequency f_{wf} of $1.67 \cdot 10^{-1}$ is assumed for the case study. Noteworthy, a unit probability that the wildfire reaches the plant is considered.

Well-established literature models were used to perform the consequence analysis of each scenario [53–55]. For exemplification purposes, a single set of meteorological conditions was considered: a uniform wind distribution and neutral atmospheric stability (wind speed at 5 m/s, Pasquill class D) [55,56]. Clearly, additional meteorological conditions should be considered to perform a complete assessment of the vulnerability. A uniform population density of 100 people/ha and a presence probability of 60% was assumed for societal risk calculations.

4.4 Results

In the present section, the application of the methodology to the case study is presented (Section 4.4.1). Then, a comparison of the developed methodology with the general methodology proposed by Cozzani et al. [20] for the evaluation of Natech and domino accidents is performed in Section 4.4.2. Section 4.4.3 provides the results obtained considering a possible delay in the emergency intervention time.

4.4.1 Application of the developed methodology to the case study

Section 4.3 reports the data required for the characterization of the wildfire scenario (Step 1.1 in Figure 4.1). The assessment of the impact vector was carried out according to Section 4.2.1.2 (Step 1.2 in Figure 4.1). The incident radiation on each target due to the wildfire $IR_{wf \rightarrow i}$ was calculated through Eq. 4.2, and the results are reported in Table 4.4.

The dynamic assessment of primary Natech and domino escalation scenarios started with the initialization step (Step 2.1 in Figure 4.1). The list of target *T* consists of all tanks present in the case study. All elements of the ***S*** and ***TD*** vectors were set to "*vulnerable*" and 0, respectively. Eventually, the time *t* is equal to 0 and the probability *P* is 1.

The Scenario Generation *SG* function (Step 2.2 in Figure 4.1) was then applied. Being the first call of the function, the only source of thermal radiation comes from the wildfire. The time to failure of each target in "*vulnerable*" status (i.e., all tanks in the first iteration) was calculated by Eq. 4.7. The results are reported in Table 4.4, and T1 was identified as the most vulnerable tank *MVT* since it features the lower *ttf* among all considered targets. Based on the *ttf*, the failure probability P_{fail} of T1 was calculated and resulted equal to 0.839. The event tree was therefore split into two branches. The lower branch considers the case in which the tank does not fail while the upper one account for its failure. Since the ***S*** vector contains other elements in "*vulnerable*" status, the procedure continues with the calculation of the thermal dose for each tank TD_i through Eq. 4.8. Clearly, the thermal dose of the identified *MVT* is equal to the critical one TD_C.

The main results related to the first iteration are reported in Table 4.4. Noteworthy, vessels P1 and P2 have a distance from the wildfire front higher than the safety distance prescribed in Chapter 3. Hence, their time to failure is higher than the maximum duration of the wildfire. Thus, the integrity of these items cannot be compromised considering only the wildfire event, and they require other fire sources to fail.

Table 4.4. Main information related to the first call of the Scenario Generation (SG) function. The equipment item involved is reported in italic.

Tank	$IR_{wf\rightarrow i}$ **[kW/m^2]**	***ttf*** **[s]**	***S* vector [-]**	TD_i **[kJ/m^2]**
T1	*28.3*	*351*	*Protected* *On fire*	*15257*
T2	25.7	392	Vulnerable	13668
T3	23.6	431	Vulnerable	12415
T4	14.5	855	Vulnerable	7167
T5	14.1	883	Vulnerable	6944
P1	12.3	-	Vulnerable	3780
P2	13.1	-	Vulnerable	4012

Considering the lower sub-branch of the event tree, the element of the ***S*** vector related to T1 (i.e., the *MVT*) is set to "*protected*" and a new instance of the *SG* function is called with:

- ***S***: {protected, vulnerable, vulnerable, vulnerable, vulnerable, vulnerable, vulnerable}
- ***TD*** [kJ/m2]: {15257, 13668, 12415, 7167, 6944, 3780, 4012}
- *t* [s]: 351

- *P*: 1·(1-0.839) = 0.161

Being the *MVT* of the first iteration protected, no update of the intensity of incident radiation IR_i is required since the wildfire remains the only source. Hence, changes in the impact vector I_i and the time to failure ttf_i of the targets occurs only if the wildfire ends in the considered time interval.

Considering the upper sub-branch, the final outcome resulting from the failure of tank T1 should be evaluated. According to Section 4.2.2.1, catastrophic failure should be considered and immediate ignition represents the more probable scenario. Hence, the final outcome associated with the failure of tank T1 is a pool fire since the stored substance is flammable (see Table 4.2 for the characterization of each tank). Being pool fire able to trigger escalation [10], the element related to tank T1of the ***S*** vector is set to "*on fire*" and a new instance of the *SG* function is called. The thermal dose vector ***TD*** and the time *t* used in the call of *SG* are the same reported for the lower sub-branch, while the probability is equal to 0.839. For the sake of completeness, Table 4.5 reports the type of loss of containment, the hazardous property, the final outcome, and the possibility of triggering escalation scenarios for each target considered in the case study.

Table 4.5. The type of loss of containment, the hazardous property, the final outcome, and the possibility of escalation for each target of the case study.

Tank	Loss of containment	Hazardous property	Final outcome	Escalation
T1	Catastrophic rupture	Flammability	Pool fire	Yes
T2	Catastrophic rupture	Flammability	Pool fire	Yes
T3	Catastrophic rupture	Flammability	Pool fire	Yes
T4	Catastrophic rupture	Flammability	Pool fire	Yes
T5	Catastrophic rupture	Flammability	Pool fire	Yes
P1	Catastrophic rupture	Toxicity	Toxic gas dispersion	No
P2	Catastrophic rupture	Flammability	Fireball	No

Since tank T1 results in an outcome able to trigger escalation, the impact vector I_i on the other tanks present in the layout should be updated. This is done through Eq. 4.3 considering the thermal radiation from both the wildfire $IR_{wf\rightarrow i}$ and the tank on fire $IR_{j\rightarrow i}$. The thermal radiation from tanks is carried out using consequence assessment models available in the literature [53–55] considering the features of the items and the edge-to-edge distances provided in Table 4.2 and Table 4.3 respectively. The thermal radiation from each tank on the others present in the layout is reported in Table 4.6.

Table 4.6. Thermal radiation $IR_{j\rightarrow i}$ received by tank T_i from tank T_j [kW/m^2].

T_i\\T_j	**T1**	**T2**	**T3**	**T4**	**T5**
T1	-	13.2	2.7	37.5	18.4
T2	13.2	-	13.2	46.0	46.0
T3	2.7	13.2	-	18.4	37.5
T4	7.3	8.8	3.6	-	109.7
T5	3.6	8.8	7.3	109.7	-
P1	1.0	2.4	5.2	12.8	36.0
P2	7.0	3.7	1.3	52.7	18.1

The time to failure is then calculated for each item in "*vulnerable*" status and the most vulnerable target *MVT* is identified. The failure probability is evaluated and the following sub-branches are defined. Times to failure considering the development of the pool fire on tank T1 are the following: *(i)* 376 s for T2, *(ii)* 422 s for T3, *(iii)* 669 for T4, *(iv)* 762 for T5, *(v)* 3855 for P2, and *(vi)* 23363 s for P1. Differently from the previous case, the time to failure of pressurized vessels is considered due to the development of a new fire. According to these results, equipment item T2 is the new most vulnerable target *MVT*.

Completing the run of the *SG* function until its end, all the possible scenarios arising from a wildfire involving the industrial installation are defined and quantified. Figure 4.5, Figure 4.6, Figure 4.7, and Figure 4.8 report the overall event tree obtained for the case study considered, providing also the failure probability and the time to failure. The lower branch related to each tank considers the case in which it does not fail. The upper branch considers instead the case in which the tank fails. In this case, the impact vector and the time to failure are updated according to the methodology described in Section 4.2.2 in each call of the SG function. Eventually, the failed tanks in each scenario are reported together with the probability of the combination.

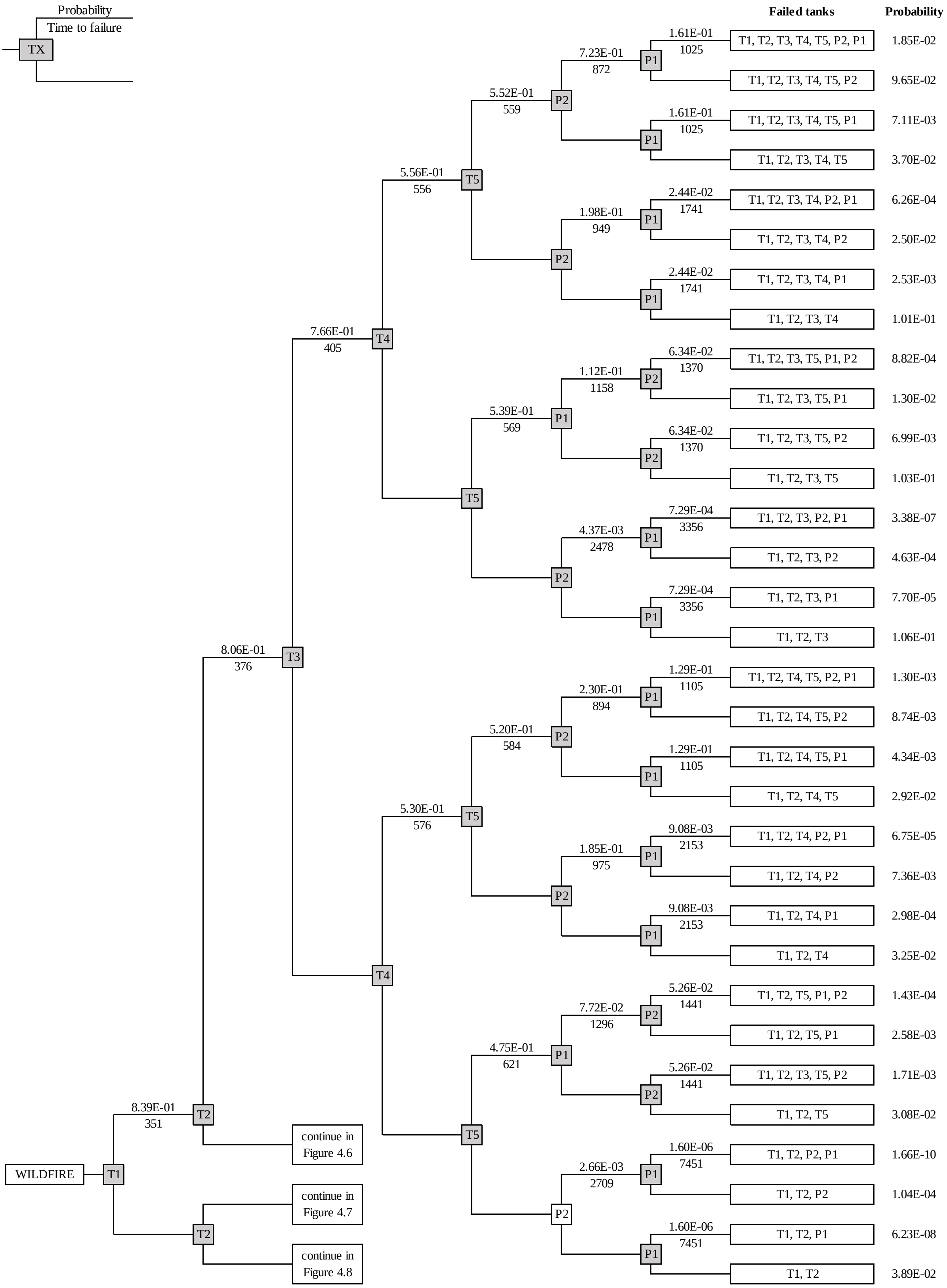

Figure 4.5. Event tree obtained by applying the SG function to the case study under analysis. The event tree continues in Figure 4.6, Figure 4.7, and Figure 4.8. The upper branch represents the case in which the tank fails. The lower branch considers the protection of the tanks.

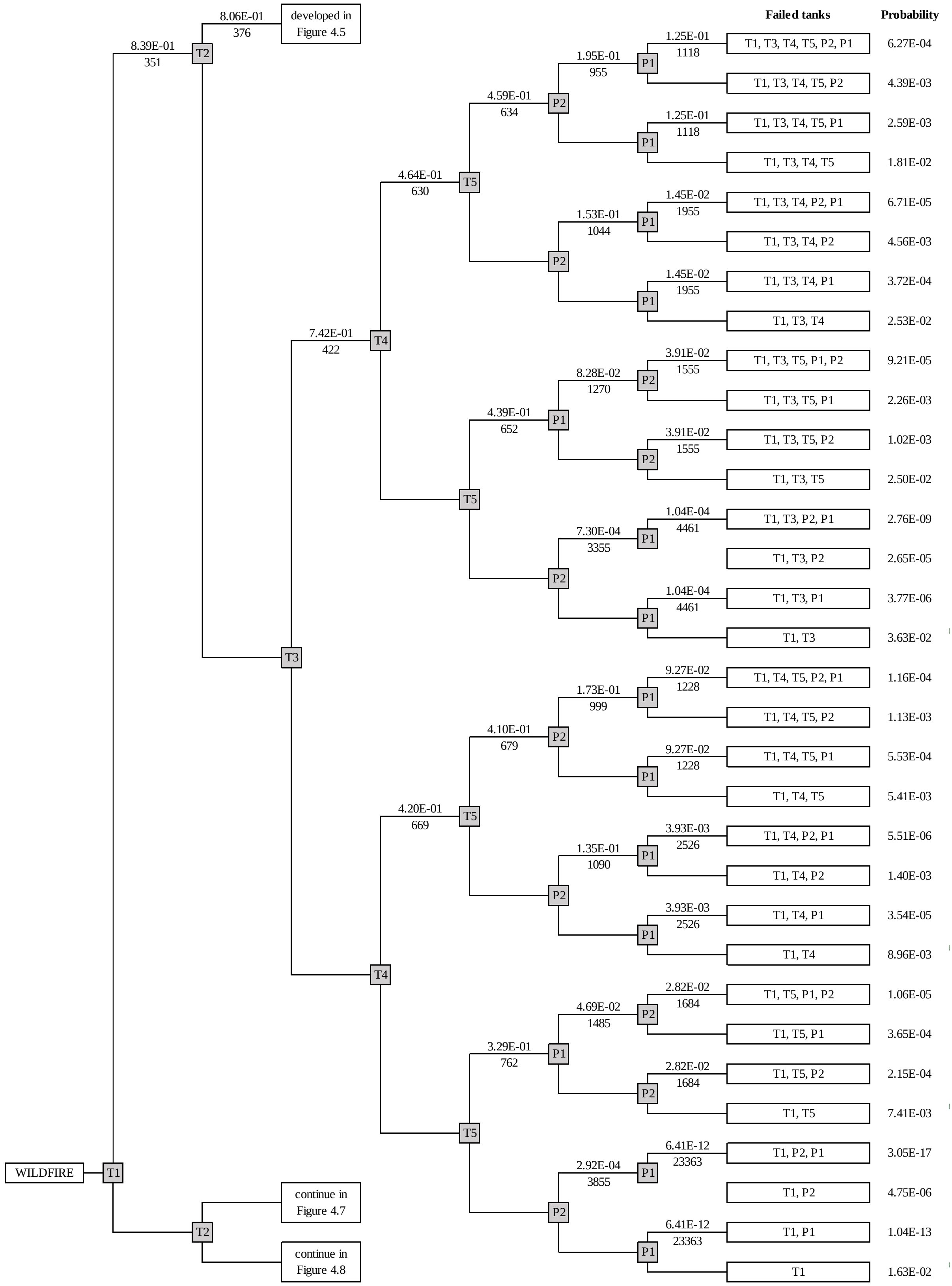

Figure 4.6. Continuation of the event tree obtained by applying the SG function to the case study under analysis. The event tree continues in Figure 4.7 and Figure 4.8. The upper branch represents the case in which the tank fails. The lower branch considers the protection of the tanks. See Figure 4.5 for the legend.

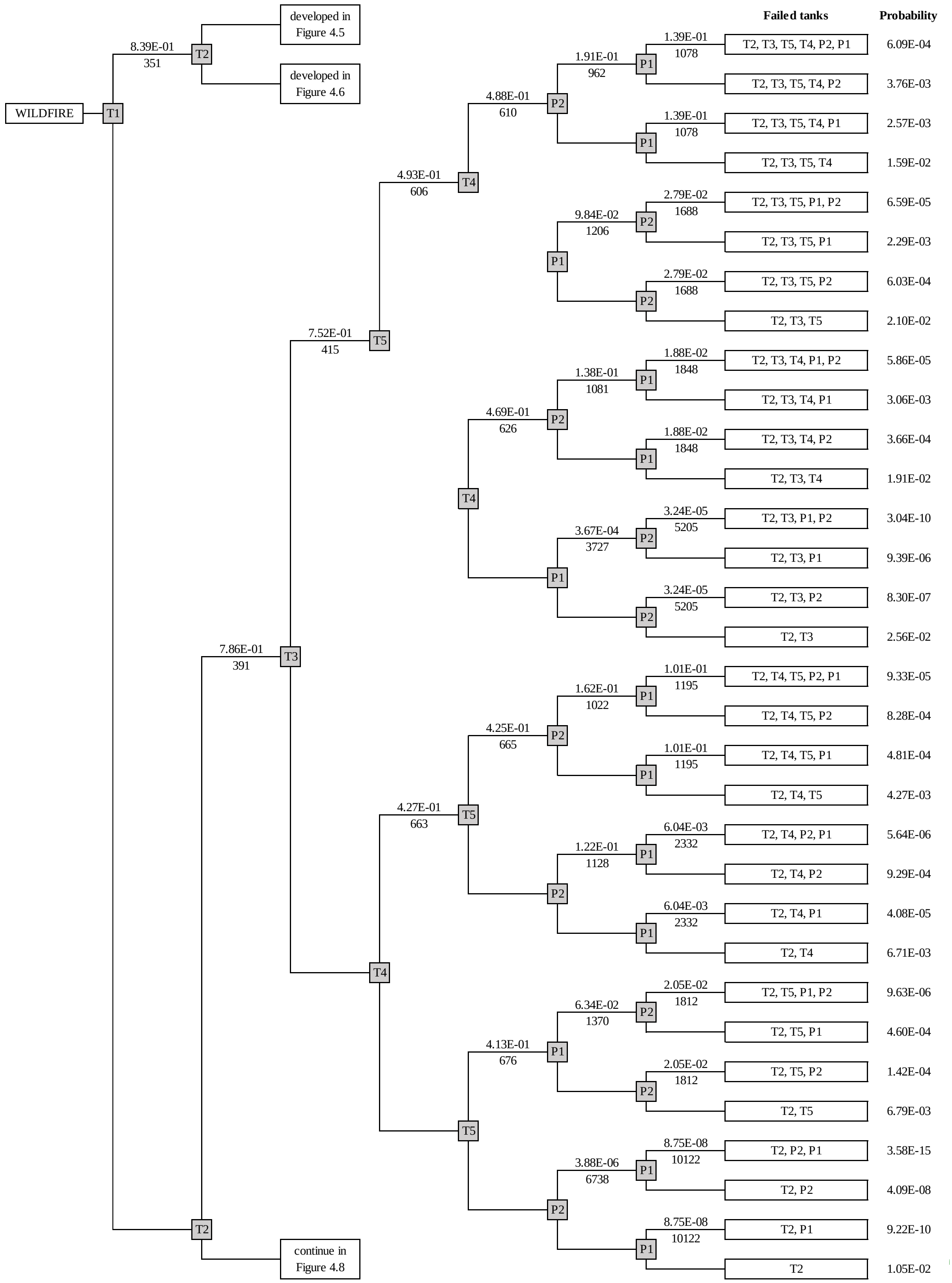

Figure 4.7. Continuation of the event tree obtained by applying the SG function to the case study under analysis. The event tree continues in Figure 4.8. The upper branch represents the case in which the tank fails. The lower branch considers the protection of the tanks. See Figure 4.5 for the legend.

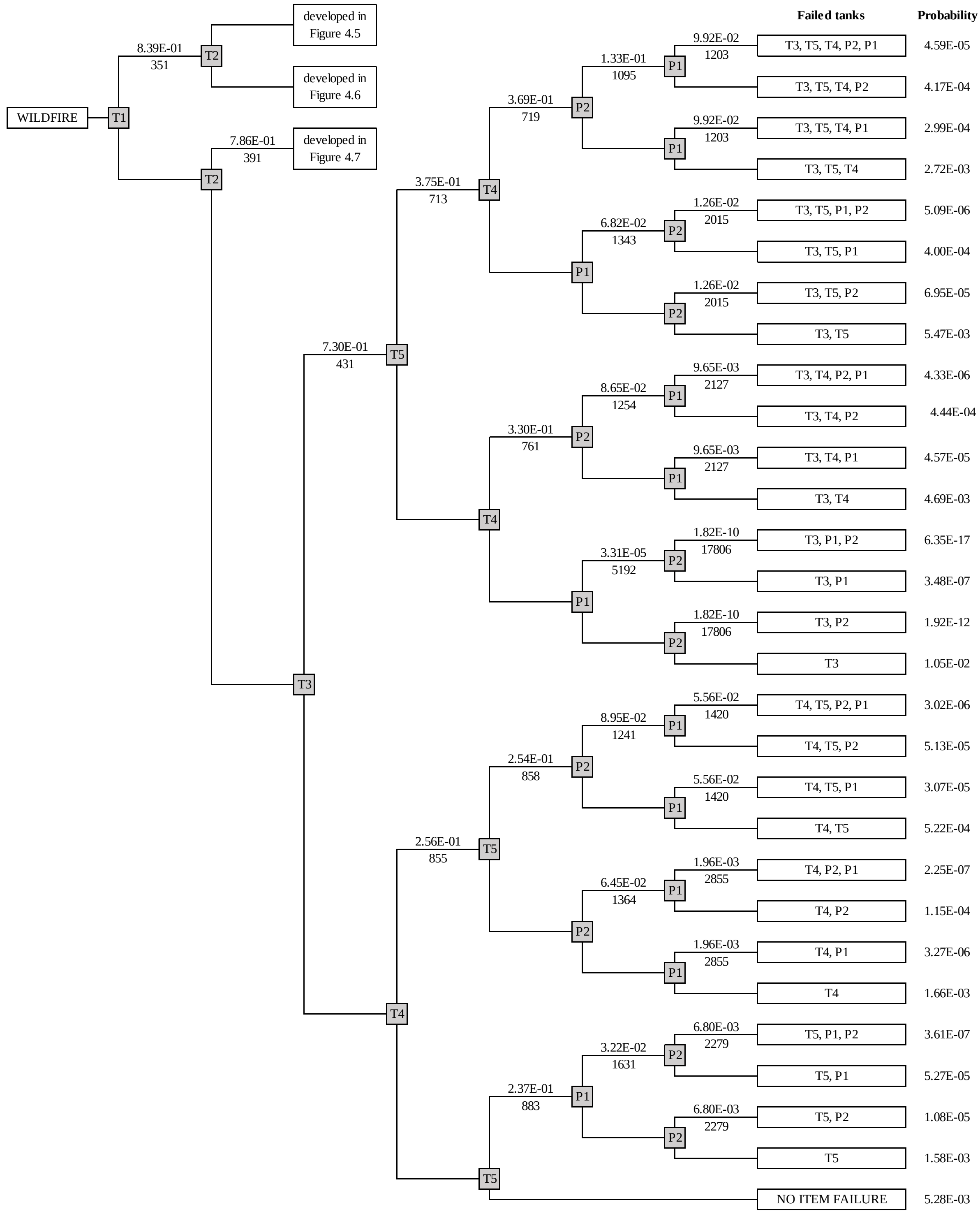

Figure 4.8. Termination of the event tree obtained by applying the SG function to the case study under analysis. The upper branch represents the case in which the tank fails. The lower branch considers the protection of the tanks. See Figure 4.5 for the legend.

A graphical representation of one of the possible fire propagations is shown in Figure 4.9. The figure is related to the chain of events in which all the equipment items fail (i.e., the upper branch in Figure 4.5). The time at which a new event occurs is reported in the figure to better understand the dynamic behaviour of wildfire-induced primary Natech and related domino escalation scenarios.

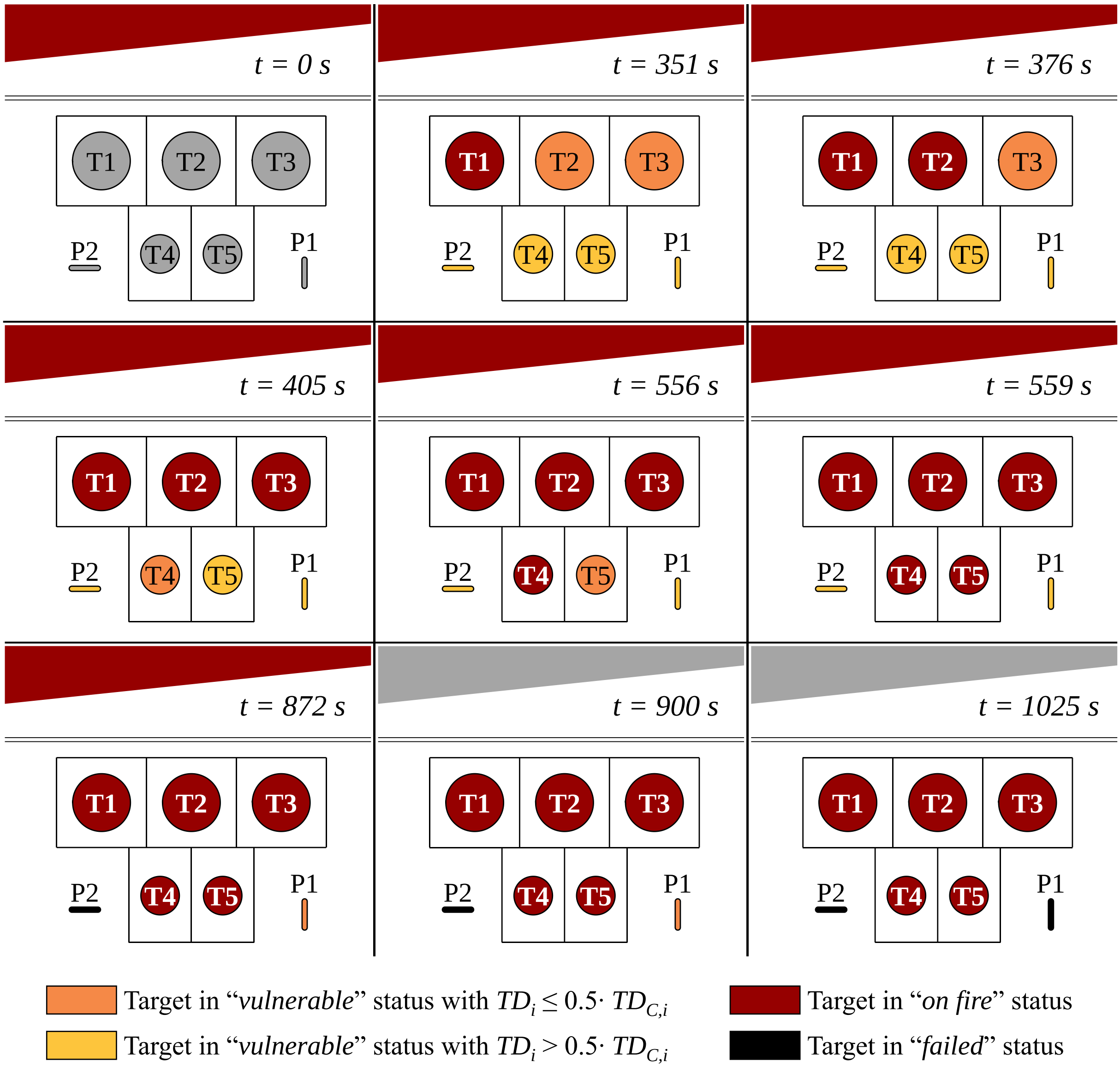

Figure 4.9. Graphical representation of the fire propagation considering the branch in which all items fail in the case study under analysis.

Once all the possible scenarios are identified, the death probability related to each scenario should be evaluated according to the procedure described in Section 4.2.3. Then, the lethality map related to the case study is calculated, and the results are reported in Figure 4.10. As can be observed, the southwestern area of the site is the most critical one. Death probabilities higher than 20% are present within the industrial site.

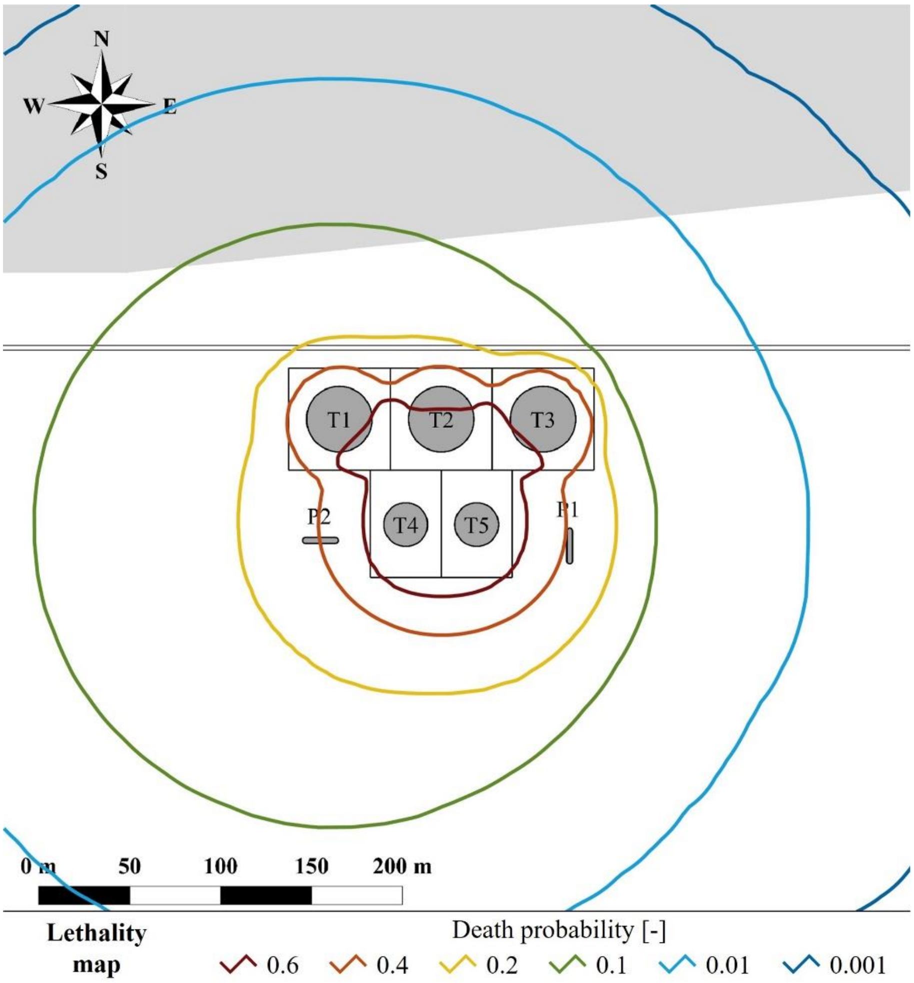

Figure 4.10. Lethality map related to the case study considered.

4.4.2 Comparison with conventional methodologies for Natech quantitative risk assessment

The dynamic methodology developed in the present study was compared to the static conventional methodology developed by Cozzani and co-workers [20] for the Quantitative Risk Assessment of Natech accidents and domino events.

The probability of simultaneous failure of a given number of equipment items was calculated considering the two methodologies. The results are reported in Figure 4.11. The probability of no failure is equal applying both approaches, being around $5 \cdot 10^{-3}$. The failure of a single item is not possible according to the conventional methodology in the case study considered. On the contrary, the dynamic approach associates with this scenario a non-zero probability. As for the failure of all equipment items, the methodology developed by Cozzani and co-workers [20] results in a probability of one order of magnitude lower than that obtained through the dynamic approach developed in the present study.

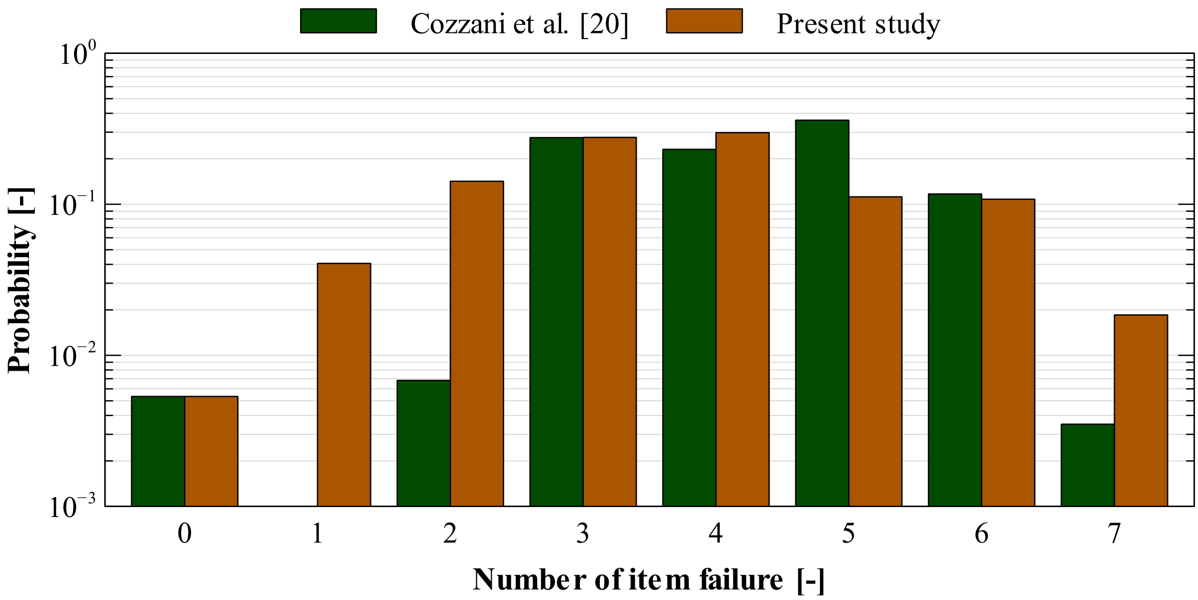

Figure 4.11. Probability of simultaneous failure of a given number of items considering the methodology developed by Cozzani and co-workers [20] *(Case 1) and the dynamic methodology developed in the present study (Case 2). See Section 4.3 for the definition of the cases.*

The lethality maps related to the case study are shown in Figure 4.12, obtained respectively by applying the static methodology available in the literature (panel a) and the dynamic approach developed in the present study (panel b). Quite similar areas related to the higher death probability (i.e., 0.6) are obtained when applying both methodologies. For all other death probabilities, the dynamic methodology (panel b in Figure 4.12) provides areas significantly larger than those obtained with the static methodology (panel a in Figure 4.12). Considering the static methodology, the green line in Figure 4.12-a encloses the area where the death probability is equal to or higher than 0.1. As for the dynamic methodology (Figure 4.12-b), the death probability is doubled for the same area. Thus, a more conservative assessment of the vulnerability of the considered industrial site is obtained by applying the dynamic methodology developed in the present study.

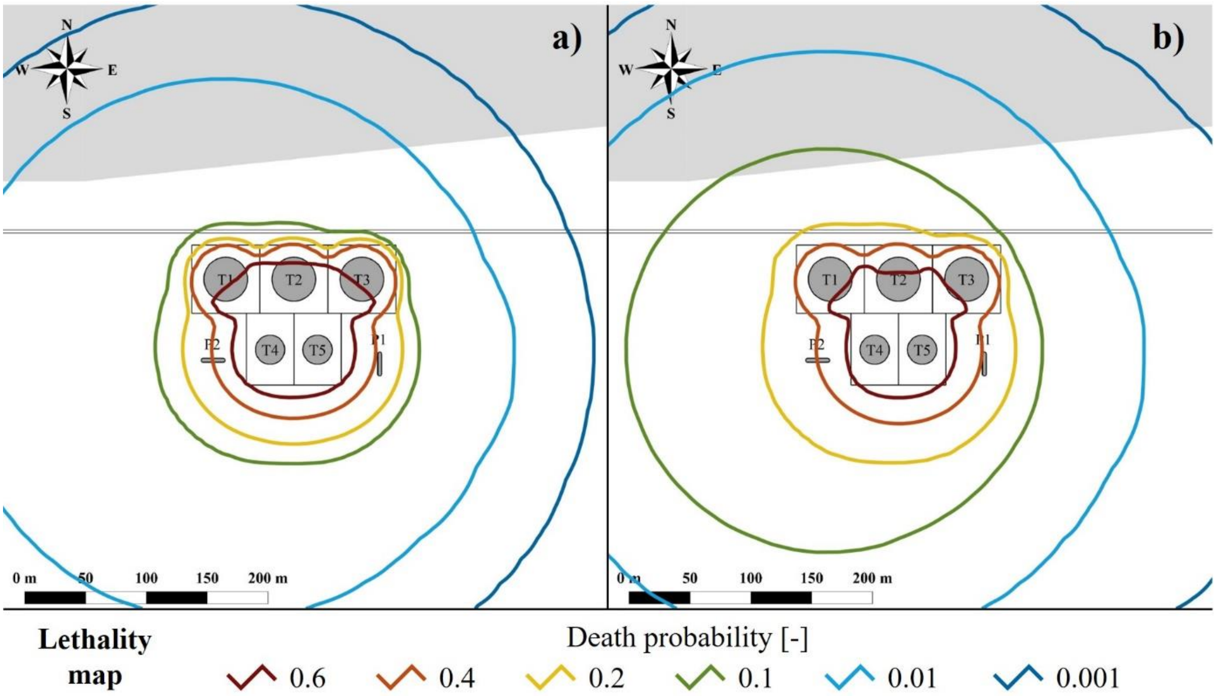

Figure 4.12. Lethality maps obtained for primary Natech and related domino escalation scenarios according to (a) the methodology proposed by Cozzani and co-workers [20] *(Case 1) and (b) the dynamic methodology developed in the present study (Case 2). See Section 4.3 for the definition of the cases.*

When coming to LSIR values, Figure 4.13 shows that the maximum order of magnitude of the vulnerability associated with both methodologies is the same, being equal to $1 \cdot 10^{-1}$. Despite this, the areas related to the intermediate values of risk are quite different. Indeed, considering for example the LSIR contour equal to $1 \cdot 10^{-2}$ (orange line in Figure 4.13), the affected area is much higher when applying the dynamic methodology developed in the present study. This highlight that neglecting the dynamic behaviour of wildfire events and related accidents can result in an underestimation of the risk.

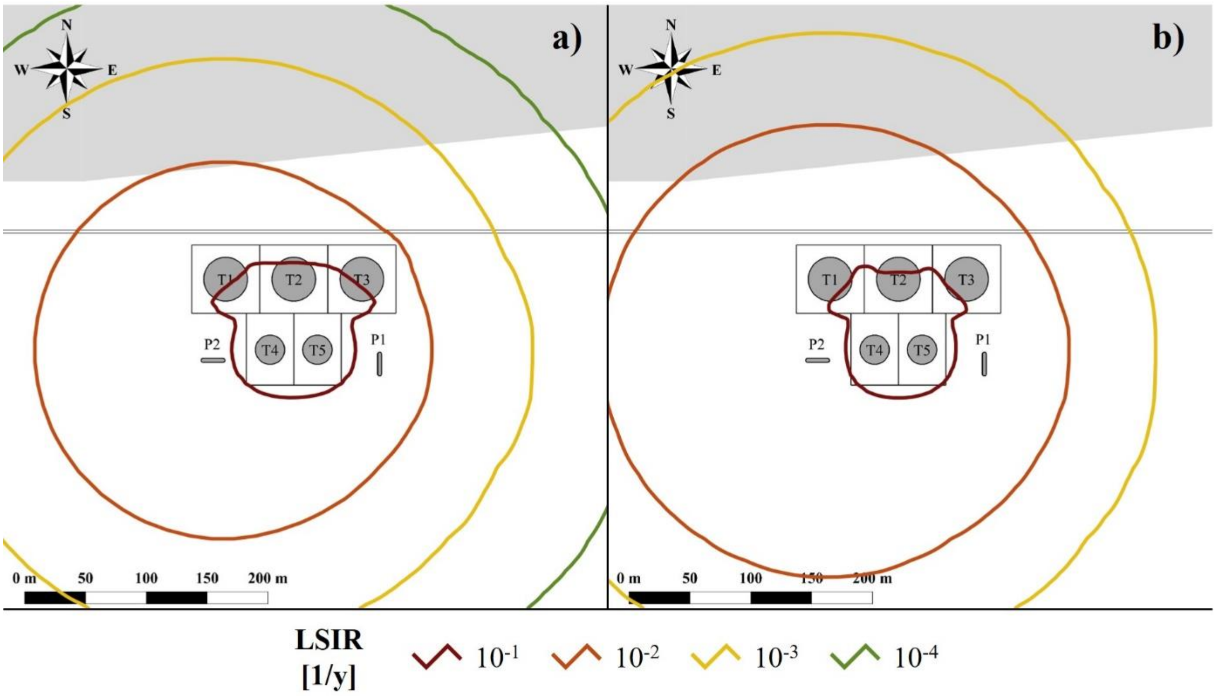

Figure 4.13. Local-Specific Individual Risk (LSIR) contours obtained for primary Natech and related domino escalation scenarios according to (a) the methodology proposed by Cozzani and co-workers [20] *(Case 1) and (b) the dynamic methodology developed in the present study (Case 2). See Section 4.3 for the definition of the cases.*

Societal risk and risk indices obtained from the two methodologies are reported in Figure 4.14. As for the societal risk, the maximum number of fatalities is the same since in both methodologies the failure of all the equipment items is a credible scenario, as pointed out in Figure 4.11. However, two different zones can be identified in Figure 4.14-a. A first zone, up to around 200 fatalities, shows that lower values of the cumulated frequency are obtained from the developed dynamic methodology. At N values higher than 200, the dynamic methodology results in higher cumulated frequencies. Higher values of the Potential Life Loss (PLL) and Expectation Value (EV) are obtained from the dynamic methodology developed in the present study, as shown in Figure 4.14-b.

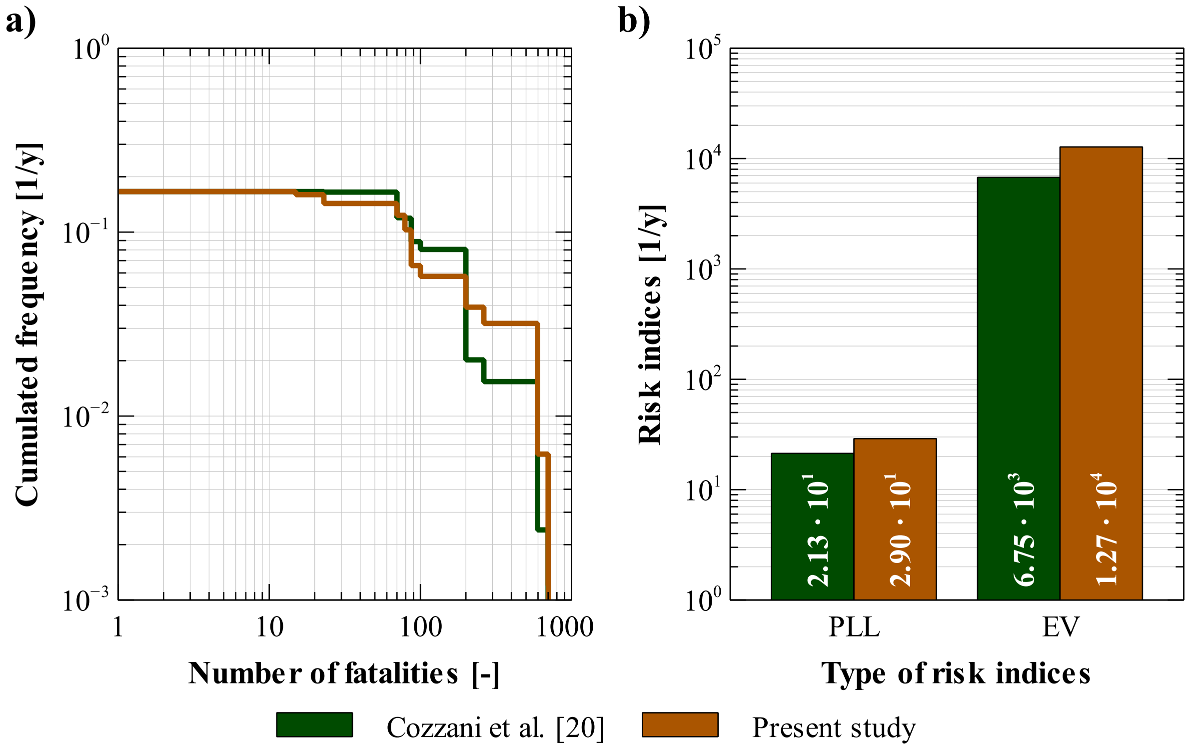

Figure 4.14. Societal risk (a) and risk indices (b) calculated according to the methodology proposed by Cozzani and co-workers [20] *(Case 1) and (b) the dynamic methodology developed in the present study (Case 2). See Section 4.3 for the definition of the cases.*

Summing up, all the results of the case-study highlight that neglecting the dynamic features of wildfire and of related technological cascading events leads to an underestimation of the vulnerability and risk related to these Natech events. Thus, the methodology developed in the present study is capable to describe more accurately the accidental dynamics and allows a more detailed evaluation of the vulnerability of facilities due to wildfire-induced accidents.

4.4.3 Comparison among different intervention time

As discussed above, the methodology developed in the present study allows for a detailed assessment of the vulnerability and risk associated with wildfire-induced Natech accidents and related domino escalation scenarios. Thus, the methodology was used to evaluate the influence of a possible delay in the intervention time of emergency teams. As discussed in Section 4.2.2.4, three different ranges were considered for the intervention time: 5-20 minutes, 7.5-30 minutes, and 10-40 minutes. Based on these time ranges, different cases were defined in Section 4.3. The case related to $\gamma = 1$ (Case 2) was already used in the previous section to compare the different methodologies in vulnerability calculation. Hence, the other two cases (Case 3 and Case 4) were evaluated following the procedure described in Section 4.2 and applied in Section 4.4.1.

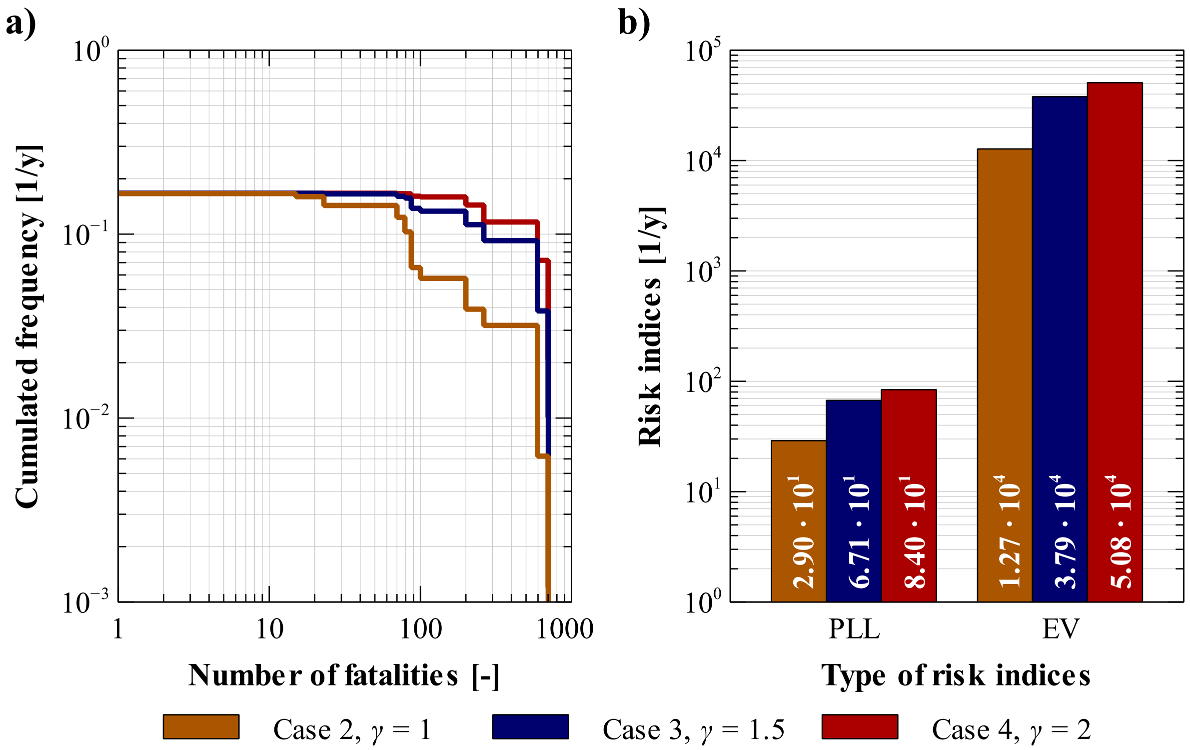

Figure 4.15. Societal risk (a) and risk indices (b) of primary Natech and related domino escalation scenarios calculated according to the dynamic methodology developed in the present study using different intervention times (see Section 4.3 for the definition of the cases)

The increase in the risk associated with a possible delay of the emergency response is evident looking at Figure 4.15, where societal risk, PLL and EV are reported for the three different intervention times considered. As for the societal risk (Figure 4.15-a), the cumulated frequency increases with the increase in the intervention time. Noteworthy, the intervention time does not influence the maximum number of fatalities since no additional failure of items occurs. The Potential Life Loss (PLL) and Expectation Value (EV) also increase due to the delay of the intervention time (Figure 4.15-b).

Overall, a delay in the emergency response has a clear negative influence on the risk of cascading events triggered by wildfires. Thus, neglecting the possible influence of wildfire events on emergency intervention leads to an underestimation of the risk.

4.5 Discussion

The present study provides a methodology for the evaluation of the vulnerability of industrial sites exposed to wildfires. The methodology accounts for both the primary Natech accidents and the related cascading scenarios, considering the dynamic behaviour of wildfires and of technological scenarios.

An important aspect of the methodology developed is that each combination derives from a single chain of events defined according to the time to failure *ttf* of targets. Thus, the proposed approach enables the description of Natech escalation patterns accounting for the dynamic aspect of wildfires. Indeed, the proposed approach considers the time dependence of the events.

It is worth mentioning that the overall number of scenarios considered by the present methodology and the static Natech QRA methodology are the same. Indeed, the number of scenarios defined by the present methodology can be calculated through Eq. 4.16 considering that only binary conditions for the targets are assumed in the methodology (i.e., the target is protected or it fails):

$$S_{tot} = 2^{n} - (2^{u} - 1) \quad \text{Eq. 4.16}$$

where S_{tot} is the overall number of scenarios, n is the number of targets present in the layout, and u is the number of targets present in the layout that cannot be affected by the wildfire event only. In the case in which all the items considered can be directly affected by the wildfire event (i.e., $u = 0$), Eq. 4.16 results equal to that derived for the estimation of the number of combined scenarios considered in Natech events by the static QRA method [20,21,26,69].

The results presented demonstrate the importance of the intervention time in the vulnerability assessment, showing a significant increase. As introduced in Section 4.2.2.4, this aspect becomes particularly relevant dealing with Natech accidents. Indeed, natural events may hamper and delay the emergency response [80–82]. Hence, an accurate evaluation of the intervention time is paramount to properly quantify the vulnerability and risk. For this reason, Chapter 5 will be dedicated to the assessment of the emergency response performance in the case of cascading events caused by Natech accidents.

4.6 Conclusions

The increasing number of natural events and disasters is posing new challenges for industrial sites in terms of safety and risk, making paramount the account of natural events as triggering factors of technological accidents (Natech). Among others, the increasing number of extreme wildfires together with the rapid extension of Wildland-Industrial Interfaces are promoting the conditions for the spread of fire front inside industrial sites triggering major accidents (e.g., fires, explosions, toxic cloud dispersions), escalating the consequences of the wildfire. Thus, neglecting wildfire-induced accidents in the QRA may significantly underestimate the risk associated with industrial plants located in wildfire-prone areas.

The methodology developed in the present study allows for the vulnerability assessment of industrial sites exposed to wildfire-induced primary Natech and related domino escalation events. The methodology considers the specific behaviour and the intrinsic dynamic features of wildfire events and resulting cascading events. Indeed, the methodology accounts for all the credible chain of events that may arise by an industrial site exposed to wildfire, considering the synergistic effect of several simultaneous fires. The methodology developed provides results that can be integrated into those obtained from the methodologies available in the literature for the static QRA of Natech scenarios.

The comparison between the present methodology and the static QRA approaches shows that existing approaches are not adequate to cope with the specific aspects of wildfire. Moreover, the results evidenced the importance of emergency intervention time in the assessment of vulnerability.

4.7 References

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Chapter 5:
EMERGENCY RESPONSE IN CASCADING SEQUENCES TRIGGERED BY NATURAL EVENTS

The emergency response is a procedural safety barrier of paramount importance in fire-driven cascading events. When these events are started by a natural event, the natural event may also affect the emergency response, hampering it. Indeed, emergency responders have to face both the natural event and the cascading technological scenario. Despite the criticality of the issue, moderate attention was devoted to date in the literature to the study of emergency response in cascading sequences triggered by natural events. The present chapter aims at contributing to fill this gap, providing a methodology for the evaluation of the emergency response performance and time in such scenarios. In addition, the methodology allows the identification of the element of the emergency response more affected by the natural event. The results of the present chapter also provide a step forward for a more reliable quantitative risk assessment of Natech accidents.

5.1 Introduction

Cascading scenarios are events where an accident from a primary unit is propagated to other adjacent units, resulting in further damage to the plant and a significantly greater loss scenario than only looking at the primary event [1,2]. Thus, cascading events are characterized by a primary accident scenario that initiates domino accidental sequences. It propagates due to an escalation vector generated by its physical effects on secondary equipment items, possibly damaging them. Eventually, one or more secondary events occur (e.g., fire, explosion, toxic dispersion) [3,4]. The primary scenarios more frequently responsible of triggering cascading events are explosion and fire [1,2]. As for the first, the escalation can be caused by the overpressure or the impact of a fragment (projectile, missile) [5–8], while for the second the escalation modes can be full engulfment, partial impingement, or distant source radiation [9,10]. Cascading events triggered by fires were responsible of severe accidents that affected the chemical and process industry. Past accidents confirmed that fire scenarios have been the main cause of cascading events in the last fifty years [11,12]. The specific feature of escalation due to fires is the time-lapse present between the start of secondary events and the start of the primary fire. The delay in the start of secondary events is due to the damage mechanism. Indeed, time is needed to raise the temperatures of the shell and the internal fluid to a value that compromises the structural integrity of the target items [9,10]. In other escalation scenarios, as those triggered by overpressure or fragments, the secondary scenarios start almost simultaneously with the primary event [5–8]. This particular feature of fire-driven scenarios allows the emergency team intervention to be used as a procedural barrier to avoid the occurrence of cascading events. In addition, according to the literature, emergency team intervention is the most effective barrier in counteracting the fire and preventing the spread of the fire to other equipment items [11,12].

The emergency response is widely considered a procedural safety barrier [13]. Its role in risk assessment and management is paramount, as derived from the Layer of Protection Analysis [14]. The emergency response can be schematized as a sequence of procedures and actions performed to increase safety after some incident/accident has occurred. The final objective of the emergency response can be human health, the environment, or assets, as shown in Figure 5.1. Specific actions can be identified as a function of the target considered. For example, evacuation and medical aid are interventions to ensure human health, while clean-up and recovery are typically used to protect the environment. Asset protection is the third goal of emergency response. In addition to an economic aspect, protecting assets is also essential to reduce the effects on both humans and the environment. Preventing the accident from spreading to other equipment items, thus avoiding a cascading event, is important to limit the consequences of the accident. The focus of the present work is the assessment of the emergency response performance aimed at the protection of the assets, i.e., the equipment items exposed to the effect of the primary scenario.

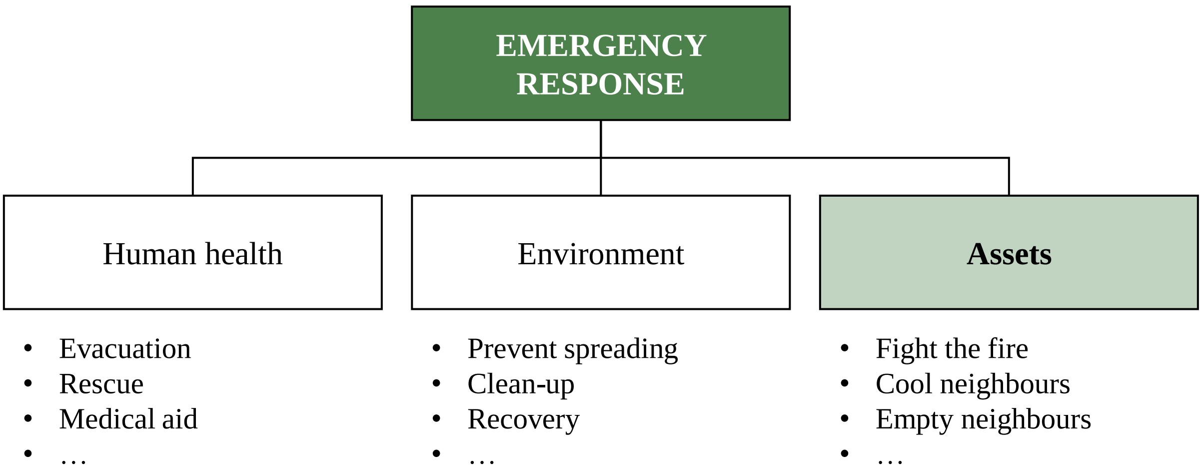

Figure 5.1. Possible targets of the emergency response. For each target, some of the possible emergency team actions are highlighted.

The emergency response becomes even more relevant in dealing with Natech accidents for two main reasons. The probability of cascading events is higher in accidents caused by natural events rather than in conventional ones, as already highlighted in Chapter 1. Moreover, past Natech accidents revealed that natural events could compromise the emergency response [15]. Indeed, the natural event hits the industrial site and the surrounding, where people, buildings, and infrastructure are present [16–18]. Thus, emergency teams have to face the consequences of the natural event itself together with those of technological accidents. Moreover, the accident probably involves large areas with several simultaneous failures, thus limiting the availability of emergency teams [15–18]. Another important factor to consider in Natech accidents is that technical barriers and equipment useful to counteract the accident can be damaged by the natural event and become unavailable [19]. Moreover, the results reported in Chapter 3 and Chapter 4 suggest that wildfire approaching industrial installations may pose severe challenges for the emergency response.

In this framework, the study of emergency response in fire-driven cascading events caused by natural events becomes paramount, and the following research questions is addressed:

Which are the effects of natural events on the emergency response?
How to measure them?

The present chapter aims to answer these research questions, providing a methodology for the evaluation of the emergency response in fire-driven cascading sequences caused by natural events (Section 5.2). The results obtained from the application of the methodology are presented in Section 5.3. In Section 5.4 some conclusions are drawn.

5.2 Methodology

The evaluation of emergency response performance and time in the case of natural events is paramount to performing a reliable assessment of the risk in the case of cascading events triggered by Natech accidents. To this aim, a methodology for the evaluation of performance modification in the case of fire-driven cascading events is proposed in the present chapter. Figure 5.2 shows the flowchart of the methodology, which consists of 5 main steps:

- Step 1: Definition of the emergency response phases, addressing the definition of the specific tasks that must be completed to effectively perform the emergency response procedures.
- Step 2: Definition of the emergency response factors. In this step, the emergency response activities and technical needs that can be affected by natural events are identified. Possible states are assigned to each factor based on its features.
- Step 3: Characterization of factors and phases. As for the factors, the probability of being in each of the possible states is evaluated. Dealing with the phases, the influence of the phases on the overall emergency response is characterized, together with the time required to complete them.
- Step 4: Analysis of the emergency response performance. The calculation of the emergency response performance is afforded in the case of natural events concerning conventional accidents. The quantification is performed through the use of a Bayesian Network approach.
- Step 5: Analysis of the emergency response time. Starting from the results of the Bayesian Network and from the information collected in the survey, the time related to the emergency response procedure is evaluated using a Monte Carlo simulation.

Each step of the methodology is described in detail in the following.

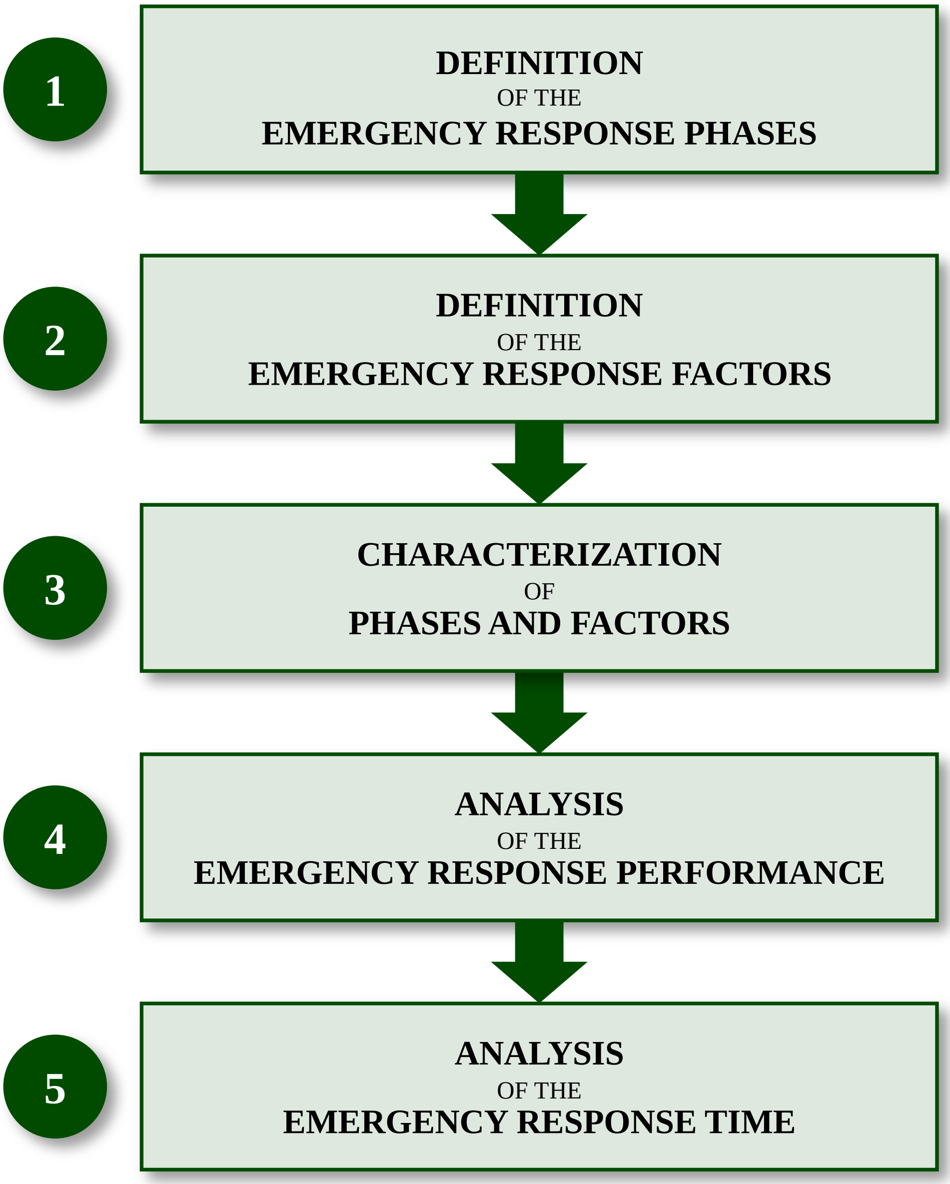

Figure 5.2. Flowchart of the methodology used for the evaluation of the emergency response performance and time.

5.2.1 Step 1: Definition of emergency response phases

As introduced previously, the study of the emergency response in the case of natural events is only marginally considered in the literature, and some examples are reported in Section 1.3.3. More attention was dedicated to the analysis of the emergency response in the case of fire-driven domino scenarios triggered by internal causes (conventional accidents). Several studies included the main aspects of the emergency response when assessing the probability of domino escalation scenarios triggered by fire, although not providing a methodology specific to the evaluation of the performance of emergency response in such scenarios [12,20–26]. Nevertheless, some of the aspects considered for the case of conventional accidents can be adopted for Natech-related accidents.

Actually, most of the previous studies divide the emergency response into a sequence of consecutive actions, each of which should be completed to effectively carry out the emergency response (Step 1 in Figure 5.2). In the present study the emergency response is thus divided into 6 phases, adopting the approach proposed by Flynn [27] and by the U.S. Fire Administration and the National Fire Data Center [28]:

- Phase 1: **Detection**. The detection phase begins when a fire develops and ends when its detection is communicated to the control room. In this phase, the capability to detect the fire is addressed.
- Phase 2: **Notification**. The notification phase starts when the control room is aware of the fire and ends when the alarm is notified to the emergency teams (i.e., the emergency teams are aware of the fire emergency).
- Phase 3: **Turnout**. The turnout phase begins when the notification of the accident is given to the emergency teams and ends when the teams leave the fire station. The turnout phase comprises donning protective gear, collecting firefighting means, and other preparatory activities.
- Phase 4: **Routing**. The routing phase goes from the moment in which the emergency teams leave the fire station to the one they reach the scene. The routing phase comprises the capability of the emergency teams to drive through external infrastructure, enter the site and reach the scene.
- Phase 5: **Setup**. The setup phase begins once the emergency teams arrive at the accident scene and ends when they start fighting the fire. Within the phase, the personnel establish the water supply, set up the necessary equipment, and perform all the needs to begin the firefighting strategy.
- Phase 6: **Fighting**. The fighting phase starts when emergency teams begin to counteract the fire (firefighting, protecting neighbouring tanks, etc.) and ends when the fire is completely extinguished.

The phases identified are schematized in Figure 5.3, where the event that starts the phase and that ends it are reported.

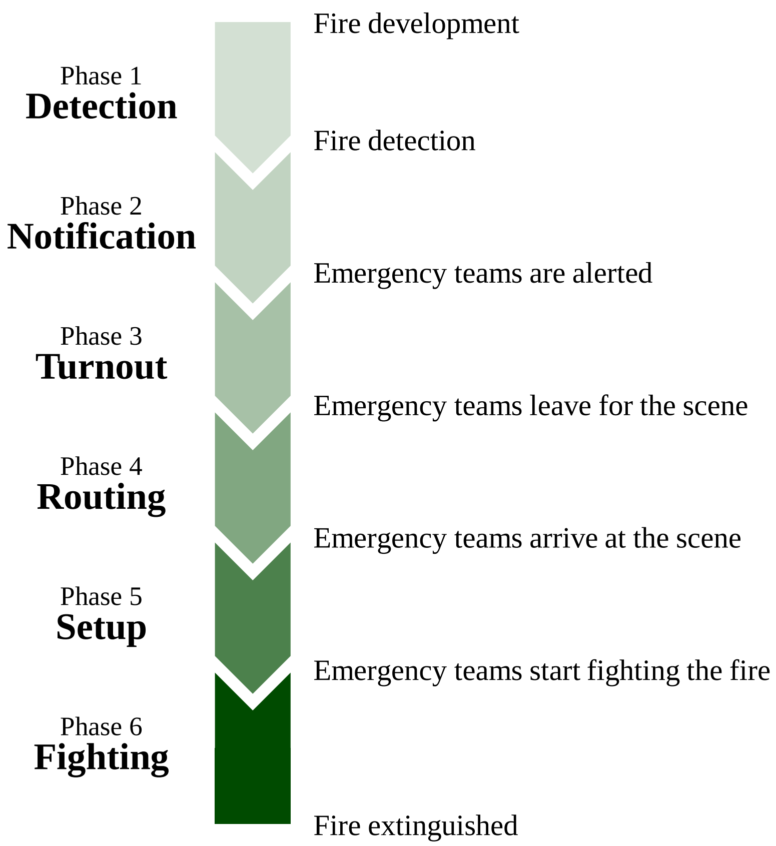

Figure 5.3. Scheme of the phases in which the emergency response can be divided. For each one, the events that begin and end the phase are highlighted.

Besides the identification of the phases, it is also necessary to define the states through which the phases can be characterized. Specifically, three states have been identified to represent the phases in the present studies, which are defined as follows:

- **Standard**. The "*standard*" status means that the phase can be concluded in standard times, thus without impediments and/or criticalities in its development.
- **Delayed**. The "*delayed*" status refers to the case in which the phase can be concluded with a certain delay in the time, thus considering the case in which impediments and/or criticalities arise that slow down the execution.
- **No**. The "*no*" status means that the phase cannot be completed.

Several response activities and technical needs are required to carry out each phase. These factors are identified and classified in the following section.

5.2.2 Step 2: Definition of emergency response factors

Once the emergency response phases are defined, the factors that may be affected by the occurrence of natural events should be identified (Step 2 in Figure 5.2). This step of the methodology was carried out by reviewing the literature and analysing major Natech accidents that occurred in the past to derive the emergency factors that were affected by natural events.

Lindell and Perry [29] have identified several criticalities related to emergency response preparedness and management in the case of hazardous materials releases triggered by the Northridge earthquake that occurred in 1994 in the San Fernando Valley (California, USA). The criticalities were mainly related to:

- Difficulties in the accessibility of the industrial site in which the hazardous material release has occurred and difficulties in the accessibility of the accident scene once on site.
- Shortages of equipment for emergency response implementation, such as firefighting equipment.
- Possible loss of firefighting materials (such as water and foam).
- Possible loss of electricity and other utility systems.
- Reduced effectiveness of communication means.
- Unavailability or shortages of qualified response personnel.

Lindell and Perry also report that the possible occurrence of multiple simultaneous accidents may exacerbate the situation, further worsening the identified criticalities [29]. Eventually, the authors also reported that threats related to aftershocks in the case of earthquakes should be considered for personnel and equipment items since they increase the probability of new or renewed hazmat releases.

Some of the criticalities identified by Lindell and Perry have also occurred in other major Natech accidents. Specifically, relevant Natech accidents triggered by the Kocaeli earthquake and the Great East Japan earthquake and tsunami were analysed in detail. Some information about these natural events and related accidents is reported in the following:

- The Kocaeli earthquake (magnitude M_w = 7.4 on the Richter scale) occurred on August 17th, 1999, and struck an area of around 41500 km^2 in Turkey, from Istanbul to the City of Bolu [30]. The affected area was densely populated and highly industrialized, and hundreds of industrial plants were hit by the earthquake leading to several accidents in the area, such as fires, toxic releases, and spills into the sea and the soil [16,31,32]. In particular, accidents at an acrylic fibre plant and a refinery in Izmit Bay were identified as the most relevant ones based on caused damages [16,17,32].
- The Great East Japan earthquake (magnitude M_w = 9.0 on the Richter scale) and tsunami occurred on March 11th, 2011, off the Pacific coast of Tohoku [32]. The earthquake affected a large part of Japan and caused the release of hazardous materials from many industrial installations [18]. In addition, the ensuing tsunami made the situation worse, damaging industrial sites and spreading released materials over vast areas [18]. Thousands of productive plants were damaged by natural events [18,33], and hundreds of hazardous material releases were reported [18,34,35]. Among all, the most relevant accidents were the one that occurred in the LPG storage tank farm in Tokyo Bay, and those arose at a refinery in the Sendai port area.

For the sake of brevity, detailed descriptions of the accidents are not reported. Additional information can be found in the reference literature on both the Kocaeli earthquake [16,17,30–32] and the Great East Japan earthquake and tsunami [18,31–35]. The analysis of these accidents allowed the identification of several shortcomings related to the emergency response, together with the identification of actions and technical needs that were affected by natural events. As a result, 8 main classes of lessons learnt were identified as follows:

- *Inadequate design of mitigation safety systems*. Namely, fire-fighting equipment items, water-based systems, and foam-based systems. As an example, the length of the hoses was not enough to reach industrial equipment located in a remote part of the site during the accident that arose from the Kocaeli earthquake. Moreover, sprinkler systems were implemented in a limited number of tanks, not accounting for 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 during the accidents that occurred after the Kocaeli earthquake. 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. In the accident analysed, the shortage of fire-fighting material affects the effectiveness of both the emergency response and safety systems, such as sprinkler systems and water deluges.
- *Damage or failure of utility systems*. Lack of the main power supply and the unavailability of the fire-fighting system (e.g., water tank pumps and pipelines) are examples of this category that occurred in both the natural events considered. The design of utility systems should consider the possible failure of primary systems, thus implementing adequate backup systems for critical elements. In addition, diesel pumps present on site were not suitable to effectively counteract the fires in the accident caused by the Kocaeli earthquake.
- *Inadequate size of the internal fire-fighting team*. This is demonstrated by the request for a multitude of external supporting teams in both the natural events considered. This assumes an additional relevance when considering that emergency teams have to face simultaneously the technological scenarios and the consequences of the natural event itself. Hence, the possible unavailability of supporting teams should be considered and properly evaluated.
- *Inadequate training for any emergency teams specific for the case of Natech accidents and related cascading events*. As reported in one of the accidents that occurred after the Great East Japan earthquake and tsunami, the emergency teams were not adequately trained to counteract the multiple fires, despite the relevant number of additional and supporting teams available at the time of the event.
- *Inappropriate emergency response plans for Natech accidents and related cascading events*. Besides the inadequate training of emergency teams, the same accident also revealed that the emergency response plan was not suitable for the several cascading events triggered by Natech accidents. Problems related to the ineffectiveness of the emergency response plan were also identified in accidents triggered by the Kocaeli earthquake.
- *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 after the Great East Japan earthquake and tsunami. The accident showed 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, thus directing new routes to reach the site.

- *Inadequate communication to effectively face natural event emergencies 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.

The lessons learned derived from the analysis of these events are valuable to address the issue of the emergency response in Natech accidents. Indeed, several elements that may be affected by natural events during emergency response activities are identified, and a summary is reported in Table 5.1. All these elements should be considered in analysing the performance of emergency response during cascading events caused by Natech accidents and therefore are included in the present methodology.

Table 5.1. A synoptic table containing the emergency response elements identified according to accidents that occurred after the Kocaeli earthquake and the Great East Japan earthquake and tsunami. Adapted from Ricci and co-workers [36].

Emergency response elements	**Kocaeli Turkey, 1999**	**Great East Japan 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

In addition to the factors already identified, some literature studies suggest that active and passive barriers may be affected by natural events, as reported in Section 1.3.3. Indeed, Misuri and co-workers focused on quantifying the effects of natural events on active and passive barriers [19]. Some of these barriers, such as detectors, are relevant from the point of view of emergency response, and therefore these should also be included in this context.

A total of 19 factors were thus identified as relevant in the evaluation of emergency response performance in the framework of cascading events caused by Natech accidents. The list is reported in Table 5.2. For each factor identified, the possible states that it may assume in the framework should be defined. The factors were therefore divided into 3 groups considering the different features of the elements:

- ***Technical needs*** (TN). This group contains all the physical equipment items necessary to carry out the emergency response procedure. Being physical equipment, they can be available or not in the case of accidents. Thus, the possible states related to these elements are "*work*" and "*fail*".

- ***Response activities*** (RA). This group includes all the elements/tasks of the emergency response that requires human actions or a series of actions. Being related to human behaviour, the states identified for this group are "*standard*", "*delayed*" and "*no*", considering the same definitions provided in Section 5.2.1 dealing with emergency response phases.
- ***Extensive needs*** (EN). Besides the characterization in terms of availability, some of the elements included in the previous group may also be represented by an extensive feature. This should consider the amount of needs available on site. Thus, elements contained within this group are represented by the states "*sufficient*" or "*not sufficient*".

Summing up, Table 5.2 reports the factors identified, the group they belong to, the acronym, the definition, and the possible states they can assume. It is worth mentioning that these factors are those considered in the development of the model for quantifying the emergency response performance and time in case of cascading events caused by Natech accidents.

Table 5.2. Factor identified as relevant for the evaluation of the emergency response performance and time. The table also reports the acronym, the definition, and the possible status they can assume.

ID	Factor	Acronym	Definition	Status
TN1	Detectors	Det	It refers to sensors located in the field to detect fire, heat, smoke, or gas leaks, and the related connection to an alarm in the control room.	Work, Fail
TN2	Cameras	Cam	It refers to items located in the field used to control the plant and the related connections to monitors in the control room.	Work, Fail
TN3	Main power supply	Main PS	It refers to the main source of power/electricity used by the plant under standard conditions.	Work, Fail
TN4	Backup power supply	Backup PS	It refers to the source of power/electricity used by the plant in situations in which the main power supply is not available.	Work, Fail
RA1	Worker availability	Worker	It refers to the possibility of workers carrying out a specific task (work tasks or procedures set out in the emergency plan), regardless of what the task is.	Standard, Delayed, No
RA2	Communication network	Com. Net.	It refers to all systems and means used by the plant to communicate a state of emergency with internal teams and external authorities.	Standard, Delayed, No
RA3	Industrial site accessibility	Site	It refers to the possibility for emergency teams to access and move within the industrial site, also through the use of vehicles.	Standard, Delayed, No

ID	Factor	Acronym	Definition	Status
RA4	Emergency team availability	ET Avail.	It refers to the possibility of at least one emergency team to respond the emergency call.	Standard, Delayed, No
TN5	Standard equipment suitability	St. Equip.	It refers to the possibility of using standard equipment and vehicles (for example, fire trucks and personal protective equipment) to reach the site and fight the fire.	Work, Fail
RA5	Additional/specific equipment availability	Add. Equip.	It refers to the availability of special or additional equipment/vehicles (for example, amphibious vehicles and specific personal protective equipment) to reach the site and fight the fire in case standard equipment is not suitable.	Standard, Delayed, No
RA6	External infrastructures accessibility	Infras.	It refers to the possibility for emergency teams to drive along roads, bridges, and underpasses (or other external infrastructures) to reach the site, also through the use of vehicles.	Standard, Delayed, No
RA7	Accident scene accessibility	Scene	It refers to the possibility for emergency teams to get close enough to the scene of the accident to be able to fight the fire, also through the use of vehicles.	Standard, Delayed, No
RA8	Setup operation	Setup Oper.	It refers to the possibility of emergency teams being able to carry out all the necessary actions needed to start fighting the fire (for example, establishing the water supply and setting up the necessary equipment).	Standard, Delayed, No
TN6	Internal firefighting equipment availability	IFE Avail.	It refers to the possibility of using the firefighting equipment present on site to fight the fire (for example, fire monitors, hydrants, etc.). In this context, reference is made only to physical equipment, not to the availability of fire-fighting material, which is accounted for separately.	Work, Fail
TN7	Internal firefighting material availability	IFM Avail.	It refers to the possibility of using the firefighting material present on site to fight the fire (for example, water, foam, etc.). In this context, reference is made both to the presence of firefighting material and the integrity of the distribution grid.	Work, Fail
TN8	Additional firefighting	AFEM Avail.	It refers to the possibility of using the additional equipment and material	Work, Fail

ID	Factor	Acronym	Definition	Status
	equipment and material availability		present on the fire trucks that arrived on site to fight the fire.	
EN1	Internal firefighting material capacity	IFM Cap.	It refers to the quantity of material available on the site to fight the fire.	Sufficient, Not sufficient
EN2	Additional firefighting material capacity	AFM Cap.	It refers to the quantity of material available on the fire trucks that arrived on site to fight the fire.	Sufficient, Not sufficient
EN3	Emergency team number	ET Num.	It refers to the number of emergency teams available on the site to fight the fire.	Sufficient, Not sufficient

The list of factors provided only includes the more common factors relevant to emergency response in a chemical and process plant. The completeness of the above-reported list of factors was validated through interviews with experts in the field (such as firefighters). However, other factors may be identified when specific features of the emergency response are considered.

5.2.3 Step 3: Characterization of phases and factors

Given the lack of data available in the literature and the limited information available concerning the effectiveness of the emergency response in cascading sequences triggered by natural events, the quantitative characterization of the factors identified in the previous sections (Sections 5.2.1 and 5.2.2) was based on expert elicitation. Expert elicitation represents a well-recognized method to obtain informed opinions from individuals with particular expertise, and it is widely applied in engineering to assess the state of knowledge concerning a specific topic [19,37].

The experts involved in the expert elicitation carried out in the present study are safety managers of industrial sites and experienced firefighters with a specific experience concerning emergency response in chemical clusters and industrial plants. It is worth mentioning that the selection of experts was made in line with the definition of expertise provided by O'Hagan and co-workers [38], who suggest that expertise does not necessarily require a great knowledge of the subject matter but that experts may also be identified in persons who have the ability to organize and use that knowledge.

Once identified the possible experts, the survey was prepared and administered to the group of experts through an anonymous online form. The survey is made up of 4 sections divided as follows:

- Section 1: Respondent's background.
- Section 2: Probability assessment of the state of each factor.
- Section 3: Probability assessment of the influence of each phase on the emergency response performance.
- Section 4: Time assessment of the phases.

In the following, details on the survey are provided together with the results obtained.

5.2.3.1 Section 1: Respondent's background

The first section was introduced to investigate the background of the respondents. In this section, statistics related to the belonging institution and the number of years of experience were gathered. It is worth mentioning that such information on the background of respondents is typically considered a suitable trade-off between anonymity and objectivity in these kinds of studies [39].

5.2.3.2 Section 2: Probability assessment of the state of each factor

The second section of the survey is related to the quantitative characterization of the factors identified in Section 5.2.2. Specifically, the objective of this part is to obtain the probability of each status for each of the factors. Experts were asked to answer the questions through the verbal scale reported in Figure 5.4. A translation of the answers into numerical values was therefore carried out according to the association shown in the same figure. The choice of asking for answers on a verbal scale was selected following the approach used in previous studies [19,40], as it helps respondents to provide more intuitive answers. Eventually, the background translation into numerical values was done following the Likert-type scale proposed by Vagias [41].

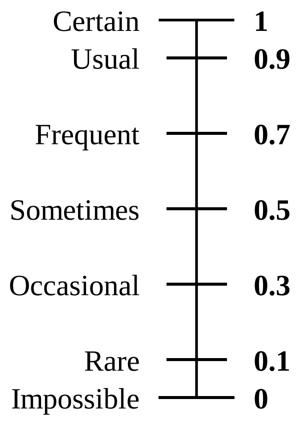

Figure 5.4. The verbal scale adopted in the survey and the related quantitative translation used in the analysis of the answers. Scale adapted from Vagias [41].

A different number of questions were posed as a function of the number of possible states associated with the factor under analysis. A brief definition of the factor was provided together with the questions, as reported in Table 5.2.

The technical needs (TN) are characterized by two states, and therefore a single question is sufficient to characterize the factor. The structure of the question used for the characterization of the technical needs is the following:

*How likely do you think **the technical need** can fail in the following accidents?*

	Certain	Usual	Frequent	Sometimes	Occasional	Rare	Impossible
Conventional accidents	○	○	○	○	○	○	○
Earthquake-induced accidents	○	○	○	○	○	○	○
Flood-induced accidents	○	○	○	○	○	○	○

Once answers are collected and converted into the numerical scale according to Figure 5.4, the probability of the status "*fail*" related to the technical need under analysis P_{fail} *(TN)* is obtained. Clearly enough, the probability of the "*work*" status P_{work} *(TN)* is obtained through the following equation:

$$P_{work}(TN) = 1 - P_{fail}(TN) \quad \text{Eq. 5.1}$$

Dealing with multiple experts, the mean values among those provided are used in the following unless otherwise noted.

Similarly, the extensive needs (EN) are also characterized by two states, and therefore the same approach described above was used. The structure of the question is the following:

*How likely do you think **the extensive needs** can be not sufficient in the following accidents?*

	Certain	Usual	Frequent	Sometimes	Occasional	Rare	Impossible
Conventional accidents	○	○	○	○	○	○	○
Earthquake-induced accidents	○	○	○	○	○	○	○
Flood-induced accidents	○	○	○	○	○	○	○

Thus, the probability of the status "*not sufficient*" of the extensive needs $P_{not\ sufficient}$ *(EN)* is derived from the numerical conversion of the answer, and the probability related to the "*sufficient*" status $P_{sufficient}$ *(EN)* is calculated as:

$$P_{sufficient}\left(EN\right)=1-P_{not\ sufficient}\left(EN\right) \quad \text{Eq. 5.2}$$

Eventually, response activities (RA) are characterized by three states. To avoid problems related to the conversion between verbal and numerical scales, it was decided to proceed by asking for the evaluation of all three possible states. Thus, three questions were formulated for each response activity whose structure is reported in the following:

*How likely do you think the **response activity** can be concluded in standard time in the following accidents?*

	Certain	Usual	Frequent	Sometimes	Occasional	Rare	Impossible
Conventional accidents	○	○	○	○	○	○	○
Earthquake-induced accidents	○	○	○	○	○	○	○
Flood-induced accidents	○	○	○	○	○	○	○

*How likely do you think the **response activity** can be concluded with delay in the following accidents?*

	Certain	Usual	Frequent	Sometimes	Occasional	Rare	Impossible
Conventional accidents	○	○	○	○	○	○	○
Earthquake-induced accidents	○	○	○	○	○	○	○
Flood-induced accidents	○	○	○	○	○	○	○

*How likely do you think the **response activity** cannot be concluded in the following accidents?*

	Certain	Usual	Frequent	Sometimes	Occasional	Rare	Impossible
Conventional accidents	○	○	○	○	○	○	○
Earthquake-induced accidents	○	○	○	○	○	○	○
Flood-induced accidents	○	○	○	○	○	○	○

After the conversion from the verbal to the numerical scale, three probability values may be obtained: probability of the "*standard*" status $P_{survey,standard}$ *(RA)*, probability of the "*delayed*" status $P_{survey,delayed}$ *(RA)*, and probability of the "*no*" status $P_{survey,no}$ *(RA)*. Since the states are assumed as mutually exclusive, the sum of the three probabilities obtained from the survey should be equal to one. For this reason, it is necessary to normalize the results obtained according to the following equations:

$$P_{standard}\left(RA\right)=\frac{P_{survey,standard}\left(RA\right)}{P_{survey,standard}\left(RA\right)+P_{survey,delayed}\left(RA\right)+P_{survey,no}\left(RA\right)} \quad \text{Eq. 5.3}$$

$$P_{delayed}\left(RA\right)=\frac{P_{survey,delayed}\left(RA\right)}{P_{survey,standard}\left(RA\right)+P_{survey,delayed}\left(RA\right)+P_{survey,no}\left(RA\right)} \quad \text{Eq. 5.4}$$

$$P_{no}\left(RA\right)=\frac{P_{survey,no}\left(RA\right)}{P_{survey,standard}\left(RA\right)+P_{survey,delayed}\left(RA\right)+P_{survey,no}\left(RA\right)} \quad \text{Eq. 5.5}$$

Noteworthy, given the diversity of the factors, the wording of the question was changed from case to case to be consistent and appropriate to the factor. However, the structure of the question and the interpretation of the results were never modified.

It should be remarked that for some of the factors, data for conventional accidents are reported in the literature [14,42,43]. In such cases, the question related to the factor for the conventional case was omitted from the survey.

5.2.3.3 Section 3: Probability assessment of the influence of each phase on the emergency response performance

The third section of the survey evaluates the influence of each phase defined in Section 5.2.1 on the overall emergency response performance. To this aim, the influence of the "*delay*" status of each phase on the overall performance should be evaluated. As for the previous section, the definition of each phase is provided together with the question. In addition, the answer is still required on a verbal scale, and the same one reported in Figure 5.4 is also used in this section. The question used for the quantification of the influence of each phase on the emergency response performance is formulated as follows:

*Considering a credible delay of the **phase** in the following accidents, how likely do you think it can lead to a cascading event/domino escalation?*

	Certain	Usual	Frequent	Sometimes	Occasional	Rare	Impossible
Conventional accidents	○	○	○	○	○	○	○
Earthquake-induced accidents	○	○	○	○	○	○	○
Flood-induced accidents	○	○	○	○	○	○	○

The answer to this question allows determining the probability that a delay in a given phase (PH) leads to a failure of the emergency response $P_{failure}$ *(PH | delay)*. Clearly enough, the probability of having a successful emergency response in the case of a delay $P_{success}$ *(PH | delay)* can be evaluated as:

$$P_{success}\left(PH \mid delay\right) = 1 - P_{failure}(PH \mid delay) \qquad \text{Eq. 5.6}$$

5.2.3.4 Section 4: Time assessment of the phases

The two previous sections of the survey were aimed at quantifying the factors in terms of probability. The last section of the survey aims to quantify the time required to carry out the operations. To simplify the problem without affecting the credibility of the assessment, the time required for each phase was addressed separately. A total of three questions were asked to characterize the time required for each phase.

The first two questions address the required time in the case of conventional accidents, which is used as a benchmark. Given the high confidence of possible responders on the topic, these questions were formulated on a numerical scale. The first question requires an estimation of a credible time range in the case of conventional accidents. In this case, a set of time ranges were proposed as possible answers and multiple ranges can be selected as long as they are consecutive. The second question requires indicating the most likely time value for the phase within the range provided. For this reason, no pre-defined time ranges were indicated as possible answers. The structure of these questions is reported in the following:

*Which is a credible time interval for the **phase** in conventional accidents?*
More than one consecutive time interval can be chosen.

○	Less than 1 minute
○	From 1 to 5 minutes
○	From 5 to 10 minutes
○	From 10 to 20 minutes
○	More than 20 minutes

*Which is the most probable time required to complete the **phase** in conventional accidents?*
Specify a value within the range provided above.

It is worth mentioning that the time ranges reported above were used to characterize the phases from detection to setup. For the fighting phases, wider ranges were defined, specifically "*less than 5 minutes*", "*from 5 to 20 minutes*", "*from 20 to 40 minutes*", "*from 40 to 60 minutes*", and "*more than 60 minutes*".

Normal distribution was selected to characterize the time required to perform each phase, and a general form of the distribution is reported in Eq. 5.7, where μ is the mean and σ is the standard deviation of the distribution.

$$\text{dist} = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot \exp\left\{ -\frac{1}{2} \cdot \left(\frac{x-\mu}{\sigma} \right)^2 \right\} \qquad \text{Eq. 5.7}$$

Therefore, the mean μ and the standard deviation σ of the distribution were calculated as a function of the answer provided in the survey by each responder for each phase. Two different approaches were applied, depending on the availability of the answer to the second question. If the responder provided the most probable value (*mpv*), the mean μ of the distribution was set equal to the provided value, and the standard deviation σ was calculated as the maximum distance between the mean and the extreme of the provided range (min_{range} and max_{range}). Eq. 5.8 and Eq. 5.9 summarise the method used for this case.

$$\mu = mpv \qquad \text{Eq. 5.8}$$

$$\sigma = \max\left\{ \left(mpv - min_{range} \right); \left(max_{range} - mpv \right) \right\} \qquad \text{Eq. 5.9}$$

Differently, if the responder did not provide the answer to the second question (i.e., the most probable value is not provided), the mean μ of the distribution was set equal to the average value of the provided range, and the standard deviation σ was set equal to half the width of the provided range. Summing up, Eq. 5.10 and Eq. 5.11 report the calculation of the normal distribution parameters in this second case.

$$\mu = \frac{max_{range} + min_{range}}{2} \qquad \text{Eq. 5.10}$$

$$\sigma = \frac{max_{range} - min_{range}}{2} \qquad \text{Eq. 5.11}$$

It is worth mentioning that all the variables reported in Eq. 5.8, Eq. 5.9, Eq. 5.10, and Eq. 5.11 always refer to a specific phase and responder. The dependence is not explicitly shown in the equations for the sake of clarity.

The last question of this section of the survey is related to the definition of the possible delay that may occur in the case of earthquake and flood-induced accidents. Differently from the conventional case, a multiplicative factor was asked to indicate the possible delay in the case of natural events rather than requiring a specific range. The question is therefore formulated as follows:

*How high do you quantify the time delay of the **phase** concerning conventional accidents considering the following events?*

	Less than 2 times	2 to 3 times	3 to 4 times	4 to 5 times	More than 5 times
Earthquake-induced accidents	○	○	○	○	○
Flood-induced accidents	○	○	○	○	○

Through the answer, the possible range of delay $delay_{range}(NE, PH, RES)$ for a given natural event is identified for each phase and each responder.

5.2.4 Step 4: Analysis of the emergency response performance

A Bayesian Network (BN) approach was selected as suitable for the quantification of emergency response performance. In the following paragraphs, some details on Bayesian Network are provided, as well as details on the BN developed in the present work to quantify the emergency response.

Bayesian Networks are a formalism broadly used to represent uncertain knowledge [44,45], and they have become widely applied in a variety of fields related to risk assessment and accident probability estimation [46–52]. Features of Bayesian Networks are the graphical encoding of conditional independence assumptions and a compact method of representing the joint probability distribution between random variables. Bayesian Networks make use of discrete random variables in their base form, even if the formalism is also broadened to continuous random variables [44,45]. Nevertheless, the present work makes use only of the discrete variable. Thus, a Bayesian Network model is a Directed Acyclic Graph (DAG) composed of nodes and arcs. The node represents the variable, while arcs represent the direct causal relationships between linked nodes [44,45]. The term "*parents*" is attributed to the nodes from which the arcs are directed, whereas the nodes with arcs directed into are referred to as "*children*". Eventually, nodes with no parents are called "*root nodes*", while "*leaf nodes*" is used to indicate nodes with no children. Each node is characterized by a finite number of mutually exclusive states, and an occurrence probability is associated with each status. In the case of children nodes, this probability of occurrence is dependent on the current states of the parent nodes directly linked to them. This is translated quantitatively through the definition of the so-called Conditional Probability Tables (CPTs), which assign the conditional dependencies between variables to each node. As a way of example, given a variable A with parent nodes $B_1, \ldots, B_n$, there exists a Conditional Probability Table that allows calculating the probability of A given the states of the parent nodes $CPT: P(A \mid B_1, \ldots, B_n)$. Eventually, the entries of the Conditional Probability Tables are parameters of the Bayesian Network.

The Directed Acyclic Graph provides a qualitative description of the Bayesian Network model, while probabilities and Conditional Probability Tables extend the model to a quantitative dimension [53].

Based on the conditional independence, d-separation concept, and chain rule, the joint probabilities of variables $V = \{X_1, \ldots, X_n\}$ are calculated through the following equation [44]:

$$P(V) = \prod_{i=1}^{n} P\left(X_i \mid \mathrm{Pa}(X_i)\right) \qquad \text{Eq. 5.12}$$

where $P(V)$ is the joint probability distribution of a set of variables V, and $Pa(X_i)$ is the set of parent nodes of X_i.

In the Bayesian Network model developed in the present study, root nodes are represented by the factors identified in Section 5.2.2. In the same section, the mutually exclusive states of each factor are also identified. Moreover, factors in the BN model represent the parent node of the nodes representing the emergency response phases defined in Section 5.2.1, which in turn are the parent nodes of the single leaf node of the model (i.e., the emergency response).

As regards the quantification of the arcs, in the present method it was decided to use a simplified approach that only accounts for the definition of the type of connection between parent nodes and children nodes. Specifically, "*AND*" connections (∧) and "*OR*" connections (∨) were used in the present approach. According to the logical meaning of the terms, the "*AND*" connection implies that all the parent nodes are in a positive status (i.e., "*standard*", "*delayed*", "*work*", and "*sufficient*") to provide a positive result. Conversely, the "*OR*" connection requires at least one positive status among the parent nodes to get a positive outcome.

The root nodes (i.e., the factors identified in Section 5.2.2) were then related to the phases according to the connections defined above. A summary of all connections among parent nodes and related children nodes is reported in Table 5.3. As a way of example, the detection phase can be concluded in three possible ways: *(i)* automatically through detectors (Det), *(ii)* remotely considering the availability of cameras (Cam), power supply (main PS or backup PS) and workers (Worker), and *(iii)* on-site which requires the availability of workers (Worker), the accessibility of the site (Site) and the availability of communication means (Com. Net.). These modes are alternatives to each other, and therefore an "*OR*" type connection is used. Acronyms are defined in Table 5.2.

Table 5.3. Connections among parent nodes and related children nodes in the BN model developed in the present study.

Children node	**Relation among parent nodes**
Detection	Det ∨ [Cam ∧ [Main PS ∨ Backup PS] ∧ Worker] ∨ [Worker ∧ Com. Net. ∧ Site]
Notification	Worker ∧ Com. Net.
Turnout	ET Avail. ∧ [St. Equip. ∨ Add. Equip.]
Routing	Infras. ∧ Site ∧ Scene
Setup	Setup Oper. ∧ [[IFE Avail. ∧ IFM Avail.] ∨ AFEM Avail.]
Fighting	[ET Avail. ∧ ET Suff.] ∧ [[IFE Avail. ∧ IFM Avail. ∧ IFM Cap.] ∨ [AFEM Avail. ∧ AEM Cap.]]

Besides identifying the type of connections, Conditional Probability Tables should be defined. Figure 5.5 reports the minimum set of Conditional Probability Tables necessary to characterize the entire BN model developed in the present work. It is worth mentioning that the probabilities of the root nodes reported in Figure 5.5 are those evaluated through the survey in Section 5.2.3.2.

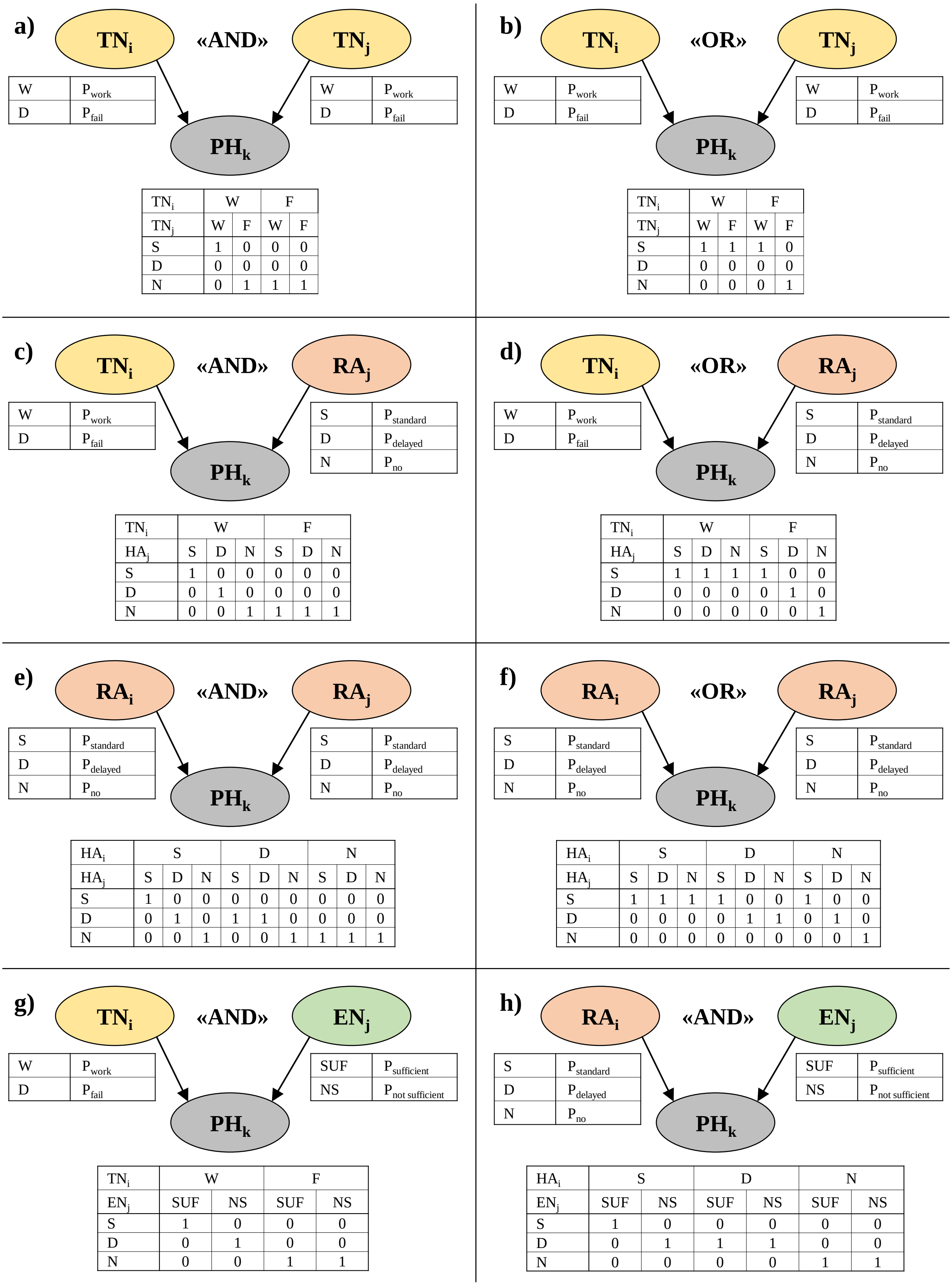

Figure 5.5. The minimum set of Conditional Probability Tables necessary to characterize the entire BN model developed in the present work.

Once quantified the three states of the phases, a binary evaluation can be introduced to simplify the assessment of their performance and the one related to the overall emergency response. As introduced in Section 5.2.3.3, the evaluation of the influence of a delay in a phase on the overall emergency response process is paramount. Thus, phases were also characterized by two state nodes, which consider only the success and the failure of the phase. Following the results of the survey presented in Section 5.2.3.2 and Section 5.2.3.3, the success probability ($P_{success}$) and the failure probability ($P_{failure}$) of a survey are evaluated as follows:

$$P_{success}(PH) = P_{standard}(PH) + P_{delay}(PH) \cdot P_{success}(PH \mid delay) \qquad \text{Eq. 5.13}$$

$$P_{failure}(PH) = P_{no}(PH) + P_{delay}(PH) \cdot P_{failure}(PH \mid delay) \qquad \text{Eq. 5.14}$$

where $P_{standard}(PH)$, $P_{delayed}(PH)$, and $P_{no}(PH)$, are the results of the three states previously associated with each phase.

Eventually, the emergency response node (i.e., the leaf node of the model) is defined as a two states node: "*success*" and "*failure*". Clearly enough, the emergency response requires that all the phases are concluded successfully. Thus, the CPT can be derived from the one presented in Figure 5.5-a.

As introduced previously, the BN is also quantified for conventional accidents, and the results represent a benchmark value for the evaluation of the performance of the emergency response in the case of natural events. Thus, results of the conventional case have been used as a normalization basis to define the performance of the single phases and the overall emergency response performance according to the following formulas:

$$\text{Performance}(PH, NE) = \frac{P_{success}(PH, NE)}{P_{success}(PH, CA)} \qquad \text{Eq. 5.15}$$

$$\text{Performance}(ER, NE) = \frac{P_{success}(ER, NE)}{P_{success}(ER, CA)} \qquad \text{Eq. 5.16}$$

where *PH* indicates a generic phase, *ER* is the overall emergency response, *NE* means that the calculation is performed in the case of natural events (earthquakes or floods) and *CA* represents the results for conventional accidents.

5.2.5 Step 5: Analysis of the emergency response time

The last step of the methodology (Step 5 in Figure 5.2) aims at evaluating the emergency response time. Specifically, the time evaluated is that starting from the development of the fire up to the beginning of the firefighting or mitigation actions performed by emergency responders. Thus, according to the definitions provided in Section 5.2.1, the phases considered in the time evaluation are detection, notification, turnout, routing, and setup. Hence, the firefighting phase is excluded from the present analysis for the following reasons:

- The duration of this phase depends on several factors. Among others, the specific features of fire that occur (such as the dimension and the quantity and type of material involved in the fire) and the number of critical equipment items nearby the primary fire. In addition, it depends on the strategy adopted by emergency teams, for example fighting the fire or cooling the neighbouring tanks, and on the number of emergency teams and the amount of firefighting material available, as identified in Section 5.2.2. All these parameters are highly specific to the scenario that has developed and to the characteristics of the industrial site in which it took place. For this reason, a generic value of the duration of the firefighting phase is difficult to evaluate and would not represent a useful result for the application to a specific industrial site, as the generic value obtained could be very far from the real one.
- Several studies in the literature make use of an intervention time for the evaluation of the failure probability of a tank exposed to an external fire [11,12,20–26], comparing it with the time to failure of the equipment item under analysis. Typically, the intervention time is defined as the time lapse between the development of the primary fire and the start of mitigation or extinguishing actions. Thus, this definition is compliant with the choice of considering only phases from detection to setup. Indeed, once the response operations have started, the emissivity of the primary fire and/or its impact vector on the other tanks is reduced. Consequently, the time to failure of the tank also changes and the comparison should be made with an updated value.

To assess the emergency response time, a Monte Carlo simulation was performed. The Monte Carlo simulation (MCS) is a numerical method that makes use of random sampling or statistical simulations. The Monte Carlo simulation requires the definition of a model that allows the calculation of the output of interest given the input variables. In addition, the MCS also requires knowledge of the variation of each input [54]. Each iteration begins with a random sampling of the input variables and ends with the evaluation of the output. This process is repeated for a defined number of replications, which is chosen as an optimum between the accuracy of the result and the computational cost of the process [54–56].

The model developed in the present study for the calculation of the emergency response time makes use of the information collected from the survey and some of the results of the BN model. Specifically, the input parameters of the model are reported in Table 5.4 together with the definition and the range of variability.

Table 5.4. Input parameters of the Monte Carlo simulation with definition, range of variability, and reference.

Input	Definition	Range	Ref
t_{CA}(PH, RES)	Time required in conventional accidents to carry out the PH phase according to the RES respondent of the survey.	dist(PH, RES)	Section 5.2.3.4
r	Numeric values that account for the probability of delay in the case of natural event-induced accidents.	[0, $P_{standard}$(PH,CA)]	Section 5.2.4
d	Delay factor related to the PH phase according to the RES respondent of the survey in the case of the NE natural event-induced accidents	$delay_{range}$(NE, PH, RES)	Section 5.2.3.4

The model defined for the Monte Carlo simulation is reported in Figure 5.6. The figure shows a single iteration of the model for a single natural event. The model returns as output the time required to complete each phase and the overall time of the emergency response in the case of conventional and Natech accidents.

Considering a given phase *PH* and a given responder *RES*, the model generates a random time value $t_{CA}(PH, RES)$. Subsequently, the model generates a random parameter *r* which is used to assign or not the delay factor in the case of natural event-induced accidents. Indeed, the value of *r* is compared with the probability of having a "*standard*" response for the phase *PH* under analysis in the case of the natural event *NE*. If the value of *r* is lower than the probability of being in a “*standard*” condition during the natural event $P_{standard}(PH, NE)$, the response is considered standard. In such case, the conventional time value $t_{CA}(PH, RES)$ is assigned also to the case of the natural event *NE*. Otherwise, the model generates a random delay factor *d* which is multiplied by the conventional time to obtain the actual time in the case of the natural events *NE*. Once the times for all the responders have been evaluated, the time of the phase in the case of a conventional accident, $t_{CA}(PH)$, and of a Natech accident, $t_{NE}(PH)$, are calculated as the average over all the responders. Once the times of all phases have been calculated, the overall time of the emergency response is calculated as the sum of all phases for both the cases considered (t_{CA} and t_{NE}).

Monte Carlo simulation

```
for PH={detection, notification, turnout, routing, setup}
 |  for all responders RES
 |   |    generate a random time value t_CA(PH, RES) from distribution dist(PH, RES)
 |   |    generate a random value r in the range [0, p_standard(PH, CA)]
 |   |    if r < p_standard(PH, NE)
 |   |    |  set t_NE(PH, RES) equal to t_CA(PH, RES)
 |   |    else
 |   |    |  generate a random value d in the range delay_range(NE, PH, RES)
 |   |    |  set t_NE(PH, RES) equal to d· t_CA(PH, RES)
 |   |    end
 |  end
 |  calculate t_CA(PH) as the mean of t_CA(PH, RES) over all responders
 |  calculate t_NE(PH) as the mean of t_NE(PH, RES) over all responders
end
calculate t_CA as the sum of t_CA(PH) over all phases
calculate t_NE as the sum of t_NE(PH) over all phases
```

Figure 5.6. Simplified algorithm defined for the Monte Carlo simulation and used to evaluate the emergency response time.

5.3 Results and discussions

This section reports the results obtained in the application of the above-described methodology, developed for the evaluation of the emergency response. Firstly, examples of results obtained from the survey are shown (Section 5.3.1). Then, the performance in the case of cascading events caused by accidents triggered by natural events is quantified through the developed BN model (Section 5.3.2). Results of a sensitivity analysis able to highlight the most critical factors with respect to conventional accidents are also presented (Section 5.3.3). Eventually, the time required to perform the emergency response in case of cascading events triggered by conventional accidents and Natech accidents is evaluated (Section 5.3.4).

5.3.1 Results of the survey

The present section presents some examples of the information collected from the survey. A total of 6 answers were collected. Clearly enough, the largest possible number of experts should be used in these analyses. Despite this, the final number of involved experts was considered acceptable since Cooke and Goossens [57] identified four as the minimum satisfying number of experts taking part in a study. Figure 5.7 shows the professional background of the experts (panel a) and their years of experience (panel b).

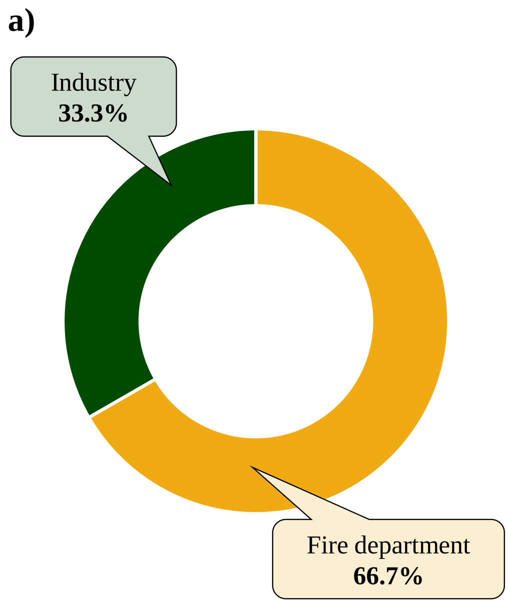

Figure 5.7. Summary of (a) the institution and (b) the years of experience (b) of the experts.

It is worth remarking that the present study aims at evaluating the emergency response as a whole. Due to the lack of quantitative data from historical analysis of past Natech accidents, the survey represents an effective route to collect information useful for quantifying the developed BN model. Although a site-specific assessment is desirable, the survey conducted in the present study allows for obtaining a general assessment of the emergency response. The analysis of the responses obtained from the survey is not a result of the present study. On the contrary, they represent the starting point for quantifying the performance of the emergency response. For this reason, only some examples of the data collected from the survey are shown in the following figures, related to the three different types of factors considered.

Figure 5.8 shows an example of results concerning the technical needs. Specifically, the probability that standard equipment typically used in emergency response is not suitable is reported (P_{fail}). As can be observed, this probability tends to zero when cascading events triggered by conventional accidents are considered. Differently, a quite higher probability is associated with cascading events triggered by Natech accidents (both considering earthquake and flood-induced accidents). In general, similar behaviour is shown for all technical needs. Obviously, the specific value changes from case to case.

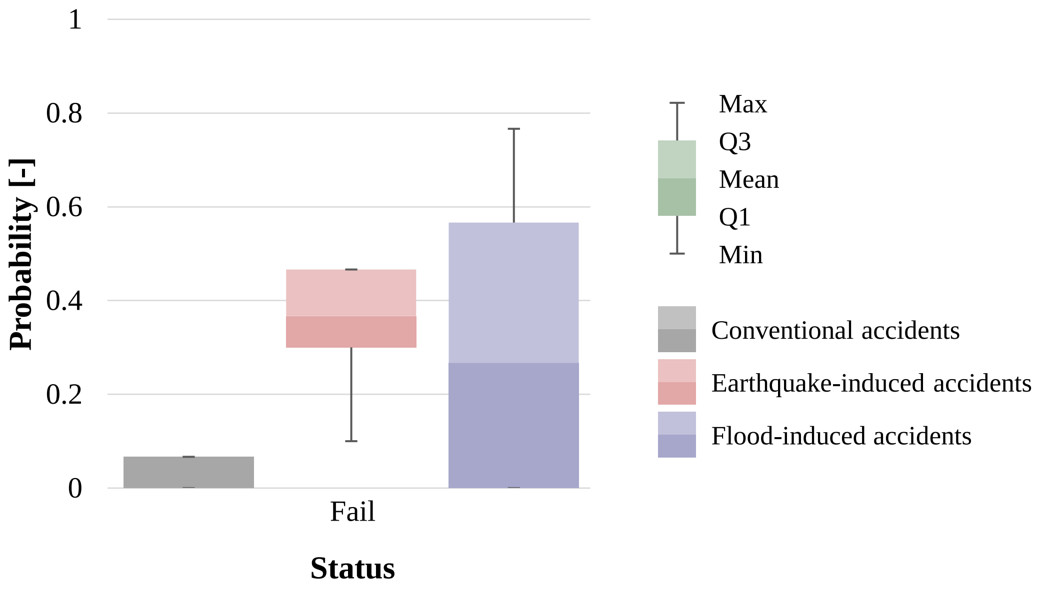

Figure 5.8. Results of the survey for the technical need "Standard equipment suitability".

An example of results concerning response activities is reported in Figure 5.9 and it is related to emergency team availability. Three results are obtained from the survey to quantitatively characterize all possible states. As can be observed, the probability of the "*standard*" status $P_{standard}$ is higher in the case of conventional accidents rather than in Natech events, while the opposite is true when considering the probability of the "*delayed*" status $P_{delayed}$ and that related to the "*no*" status P_{no}. As in the previous case, the relative trend shown in Figure 5.9 is detected for all the factors classified as response activities.

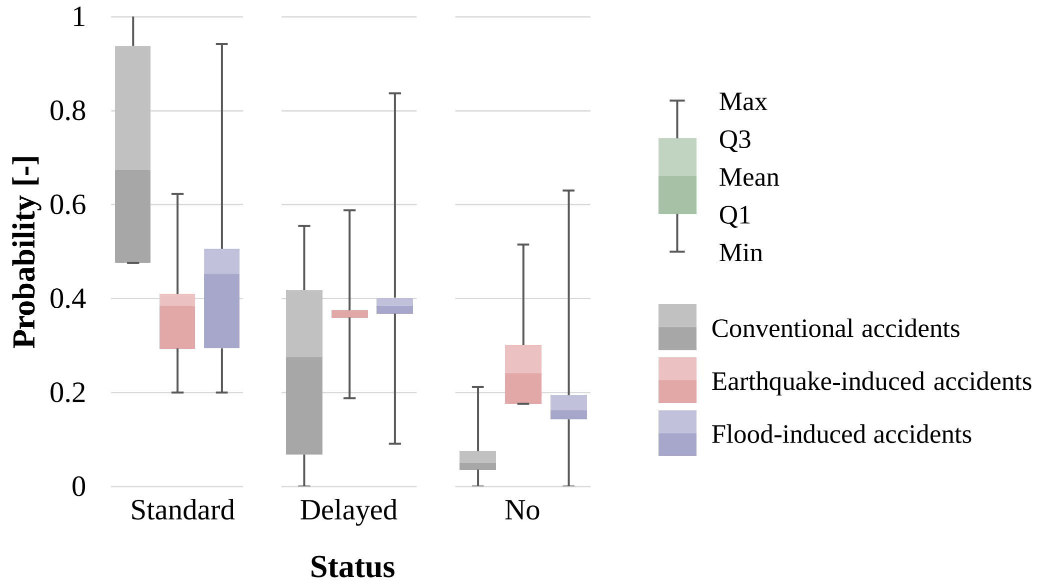

Figure 5.9. Results of the survey for the response activity "Emergency teams availability".

The result obtained for the emergency teams number is reported in Figure 5.10 as representative of the extensive needs category. Thus, the probability that the number of team members is insufficient ($P_{not\ sufficient}$) is retrieved from the survey. Similarly to the case of technical needs (shown in Figure 5.8), the probability that the need is not sufficient is lower in the case of conventional accidents, whereas a higher value is obtained in the case of Natech accidents.

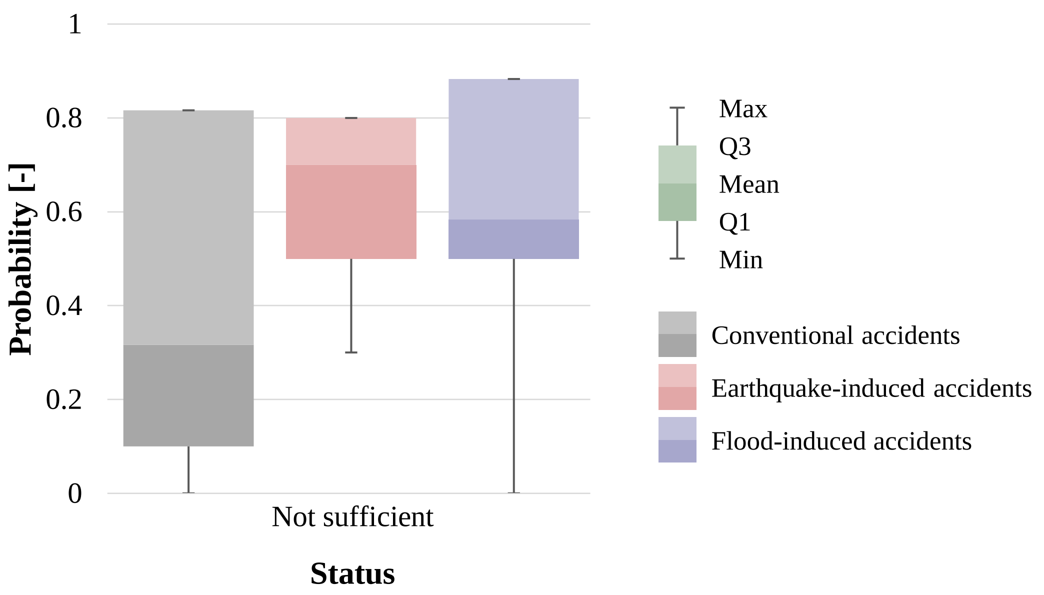

Figure 5.10. Results of the survey for the extensive need "Emergency teams number".

Besides characterizing the factors, the survey collected also information on the effects of the delay of each phase on the success of the emergency response process (see Section 5.2.3.3). The results are shown in Figure 5.11, which reports the probability of failure of each phase given a credible delay $P_{failure}$ *(PH | delay)* for the case of cascading events triggered by conventional accidents (grey bars), earthquake-induced accidents (red bars) and flood-induced accidents (blue bars). The mean values of the survey answers are reported. Looking at the figure, two possible behaviours are identified. As for the phases from turnout to firefighting, the possible delay in the case of Natech events is considered more burdensome and is therefore associated with a greater probability of failure. Among these, turnout and routing phases seem to be the most critical ones. On the contrary, a delay in carrying out the detection and notification phases seems more critical in the case of conventional accidents rather than in Natech events. However, this is not surprising considering the specificities of these two phases. Indeed, in the case of a Natech accident, the natural event itself represents the first alarm to industrial workers and emergency teams. Therefore, it is credible that the workers check the site as soon as possible and are probably already in communication with the emergency teams. Thus, the severity of a delay for these two phases is reduced, also considering the longer time required to carry out the entire emergency response operation in the case of Natech events.

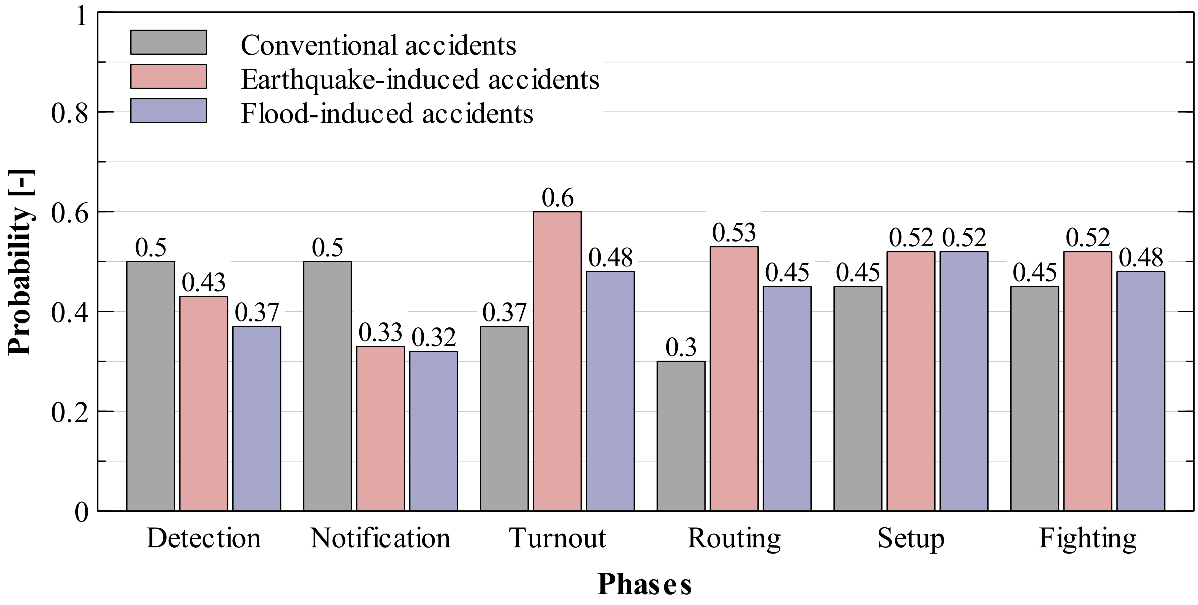

Figure 5.11. Results of the survey related to the probability of failure of the emergency response phase given a delay $P_{failure}$ (PH | delay).

5.3.2 Quantification of the BN model

The Directed Acyclic Graph of the Bayesian Network model developed in the present study is reported in Figure 5.12. Figure 5.5 and Section 5.2.4 report detailed information on the quantification of the BN model.

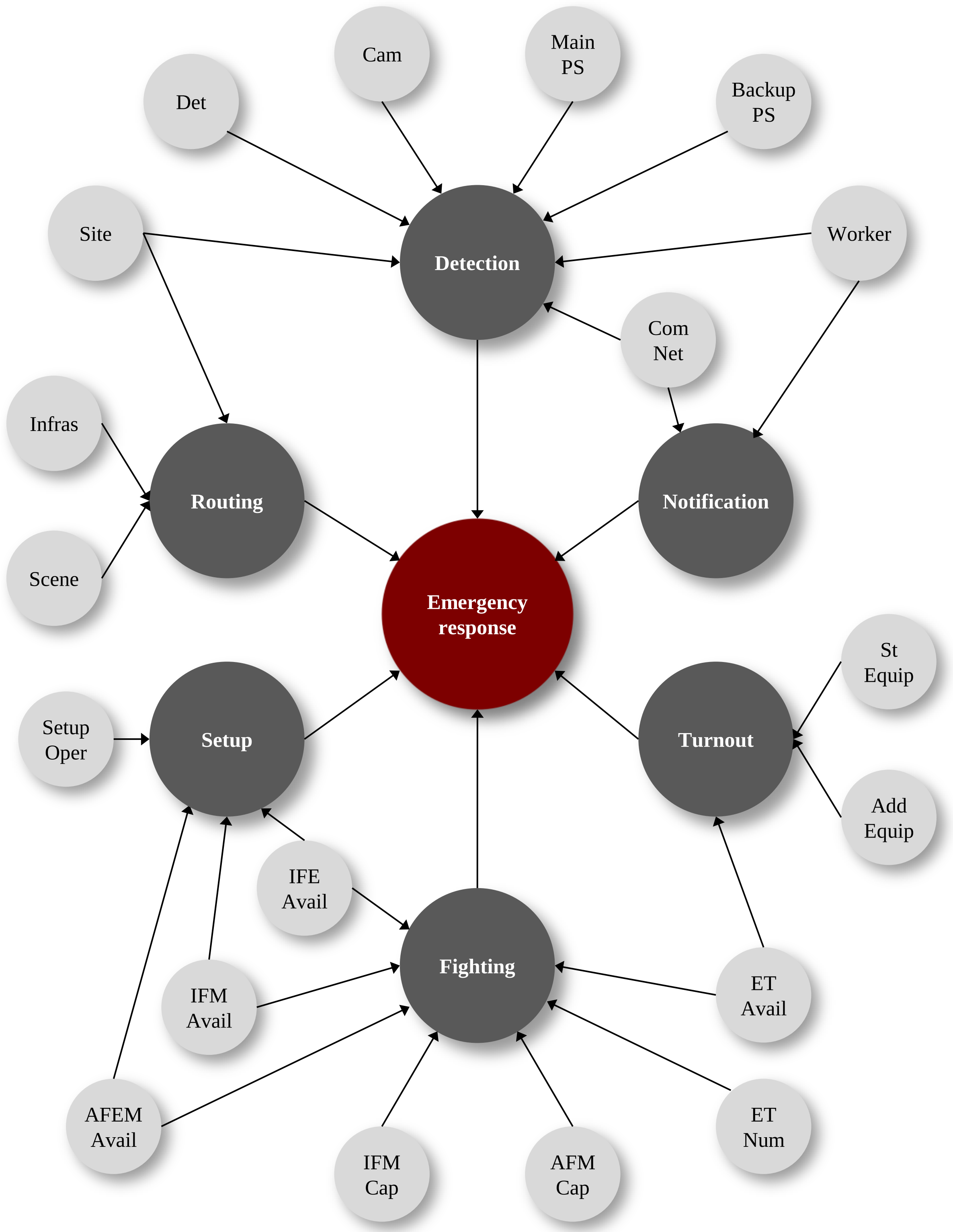

Figure 5.12. The Directed Acyclic Graph of the Bayesian Network model developed in the present study. The definitions of the factors and phases are given in Table 5.2 and Section 5.2.1 respectively. Please consider that the emergency response node can assume two states: success and failure.

The probabilities of the three states of each phase are reported in Figure 5.13 considering conventional accidents (panel a), earthquake-induced accidents (panel b), and flood-induced accidents (panel c). The figure shows the results considering the mean value from the survey responses.

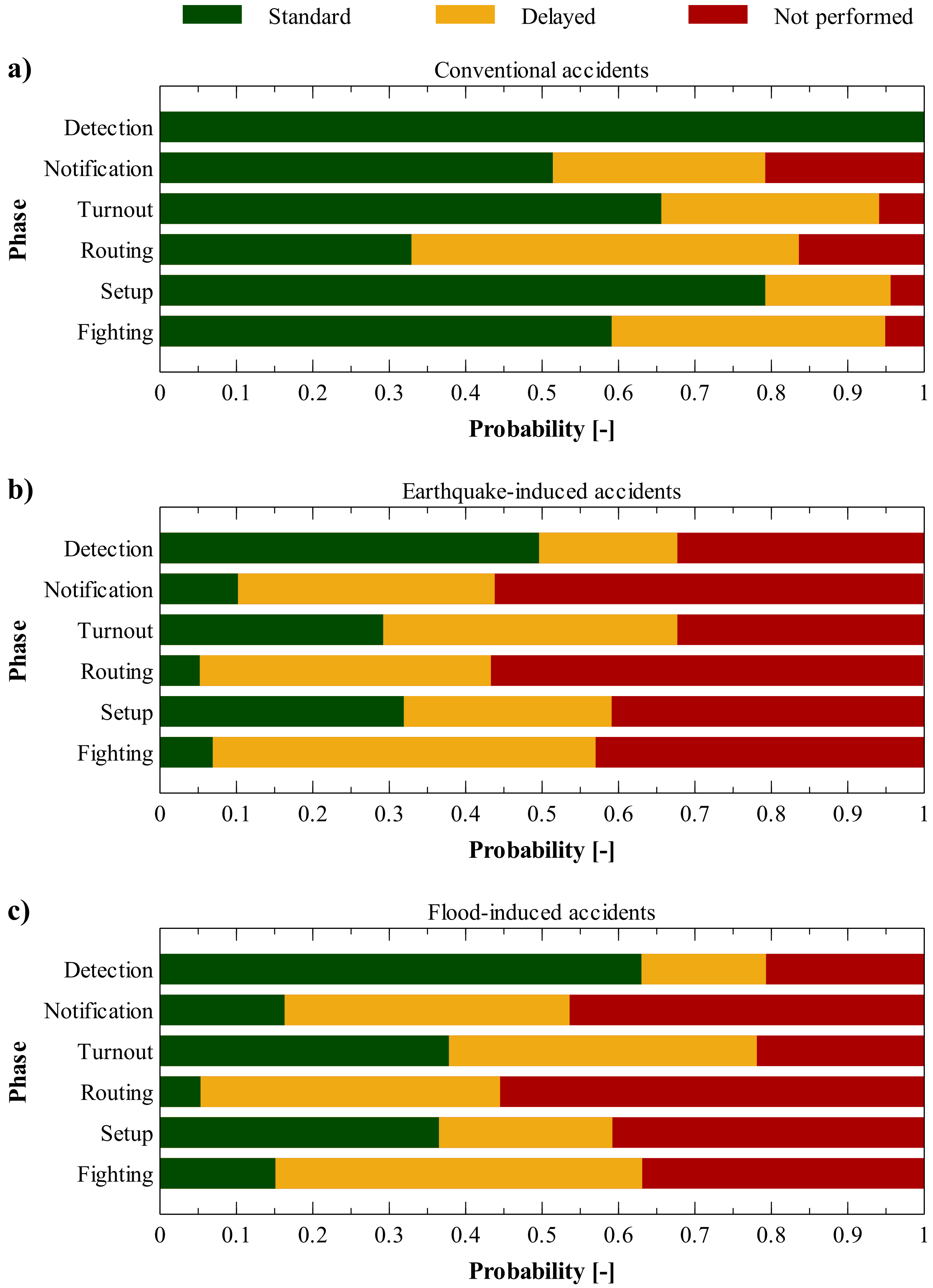

Figure 5.13. Probabilities of the three states of each phase considering (a) conventional accidents, (b) earthquake-induced accidents, and (c) flood-induced accidents. The definition of the phases is given in Section 5.2.1

Comparing the results for the three triggering events, it is clear that each phase is affected by the occurrence of a natural event, regardless if it is an earthquake or a flood. Indeed, the probability of being "*standard*" is strongly reduced in these cases, and likewise, the probability that the phase is not completed greatly increases with respect to conventional accidents. Both elements highlight the strong influence of a natural event on all phases of the emergency response.

To better visualize this result, the performance of each phase is calculated according to Eq. 5.13 and Eq. 5.15 reported in Section 5.2.4. Results are reported in Figure 5.14, where red bars refer to earthquake-induced accidents and blue bars to flood-induced ones. It is worth mentioning that the results obtained for conventional accidents and presented in Figure 5.13-a are used for the normalization of the results. As can be observed from Figure 5.14, the routing phase is the most affected when considering natural events, followed by the fighting phase and the setup phase. Thus, effort should be dedicated by site managers to improve the performance of such phases in the case of earthquakes and floods.

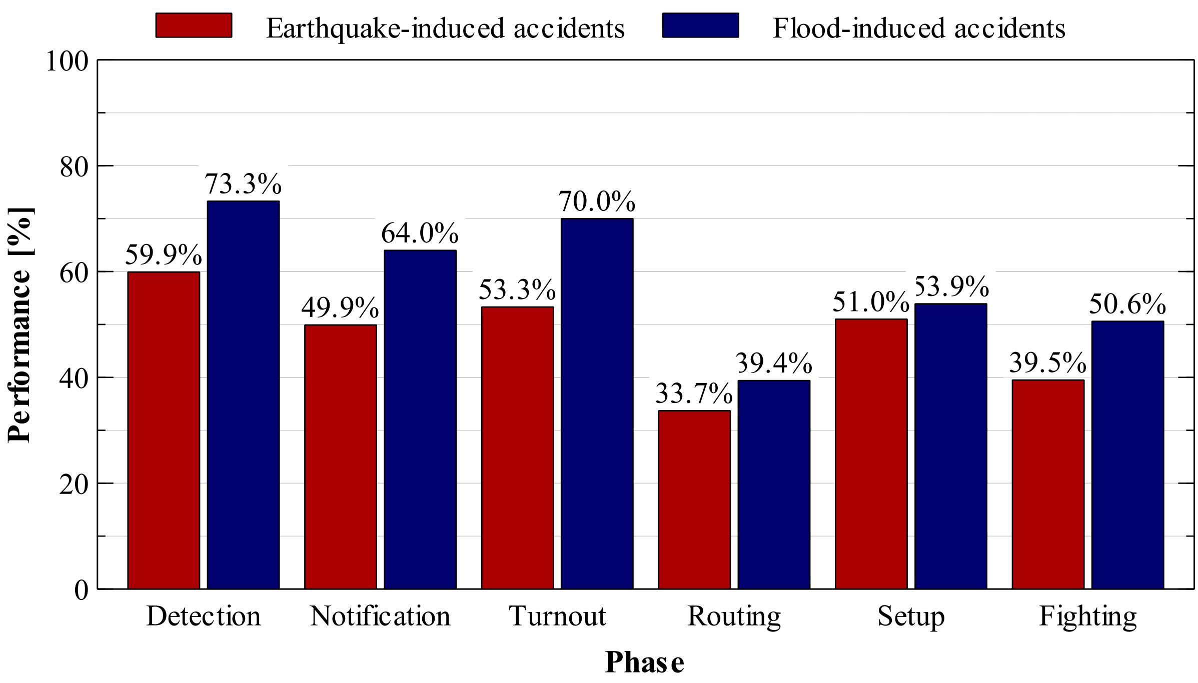

Figure 5.14. Performance of each phase in the case of earthquake-induced accidents (red bars) and flood-induced accidents (blue bars). Please consider the definition of performance provided in Eq. 5.15.

In addition, the BN model was also quantified, considering the best-case and worst-case answers obtained from the survey. Figure 5.15 shows the variability of the performance of each phase according to the results gathered from the survey. As can be seen from the figure, the performances of each phase change considerably in the three different cases. Despite this, it is important to remark that the mean value is almost always closer to worst-case than best-case, emphasizing the criticality of the problem and the need to improve the performance of the emergency response in the case of cascading events triggered by Natech accidents.

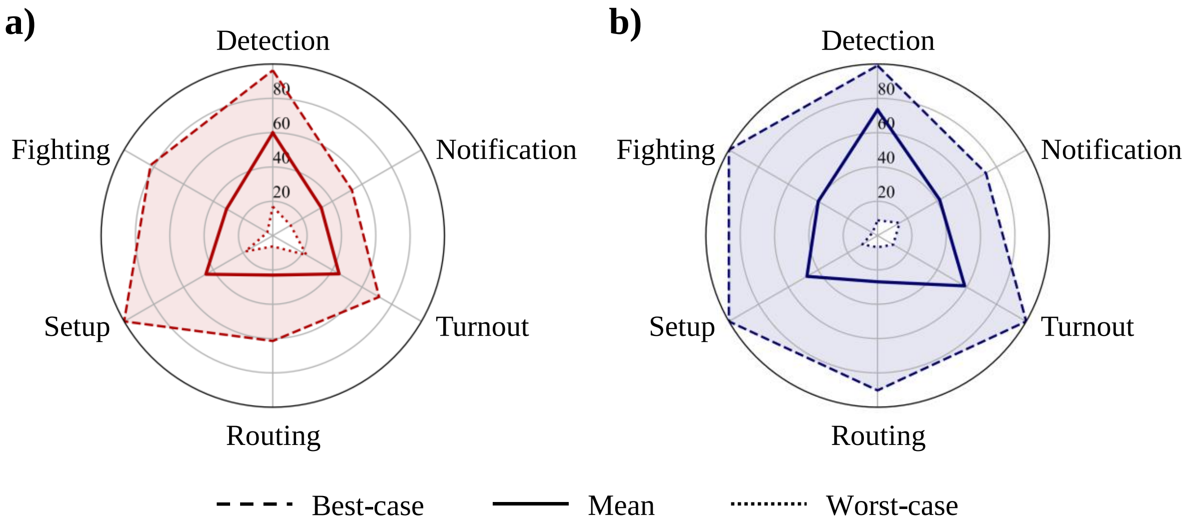

Figure 5.15. Variability of the performance of each phase for earthquake-induced accidents (panel a) and flood-induced accidents (panel b) considering the mean value from the survey, the worst-case answer and the best-case answer.

Eventually, the overall emergency response performances in the case of earthquakes and floods were also evaluated, and the results are reported in Figure 5.16 considering the mean value from the survey, the worst-case answer and the best-case answer. Overall, earthquakes affect the emergency response more than floods, leading to a lower value of the emergency response performance, as seen from the phase results. Despite this, it is essential to point out that both performance values in Natech accidents are very low (specifically, 2.6% for earthquakes and 6.6% for floods). This means that the emergency response is strongly influenced by the occurrence of natural events and that the effectiveness is far from that experiences in conventional accidents.

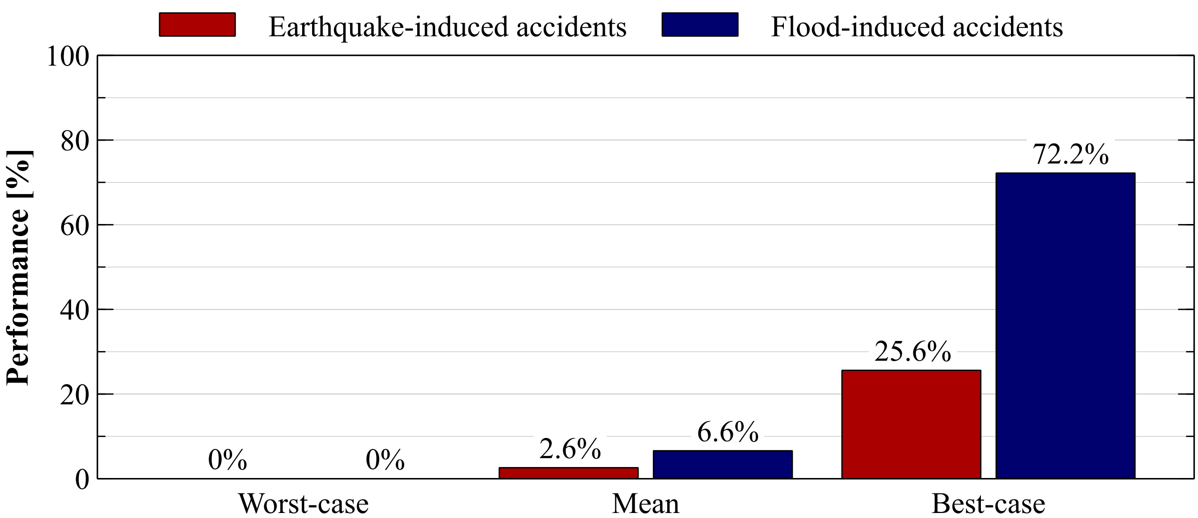

Figure 5.16. Emergency response performances in the case of earthquake-induced accidents (red bars) and flood-induced accidents (blue bars) considering the mean value from the survey, the worst-case answer and the best-case answer.

5.3.3 Identification of the critical factors in Natech accidents

The emergency response is strongly influenced by the occurrence of natural disasters, as discussed in the previous section. Thus, the identification of the critical factors whose failure or hindering may affect the specific phase of the emergency response is paramount in such cases. With this aim, a sensitivity analysis was carried out on the BN model developed in the present study. The sensitivity analysis was performed by modifying the probability of each factor one at a time considering two extreme situations:

- A lower bound (negative changes) was evaluated considering the total unavailability of the factor, which represents the worst situation.
- An upper bound (positive changes) was evaluated characterizing each factor as in the case of conventional accidents, which represents the best situation.

By this approach, the factors mostly affecting each specific phase of emergency response in the case of Natech accidents are identified. Figure 5.17 and Figure 5.18 report the results of the sensitivity analysis on each phase in the case of earthquake-induced accidents and flood-induced accidents respectively. The probabilities used in the analysis are those related to the mean values obtained from the survey.

The factor mostly affecting the detection phase is the availability of detectors for both the case of earthquakes and floods (panel a, Figure 5.17 and Figure 5.18). The influence of the other factors on the detection phase is moderate to the availability of detectors, and there are no relevant differences between earthquakes and floods. As for notification and turnout phases, no differences are present between earthquakes and floods (panels b and c respectively of Figure 5.17 and Figure 5.18). In addition, the two elements related to the notification phase (the communication network and the worker availability) seem to affect the phase similarly. On the contrary, the emergency team availability affects the turnout phase much more than the suitability of standard equipment and the availability of additional ones. The results obtained for the routing phase are reported in Figure 5.17-d and Figure 5.18-d. Indeed, the accessibility of the external infrastructure is the most influencing factor in the case of earthquakes, whereas in flood events the phase is more affected by the accessibility of the site. Even if the difference in quantitative terms is moderate, the results allow for identifying the factors toward which the attention should be devoted with higher priority. Concerning the setup phase (panel e, Figure 5.17 and Figure 5.18), the capability of performing the setup operation is the most important factor, and a similar trend can be observed for all factors in the case of earthquakes and floods.

There are no substantial changes regarding the fighting phase among earthquakes and floods (panel e, Figure 5.17 and Figure 5.18). In both cases, the availability of emergency teams and additional firefighting equipment and material are the most critical factors, while the other factors have a lower influence.

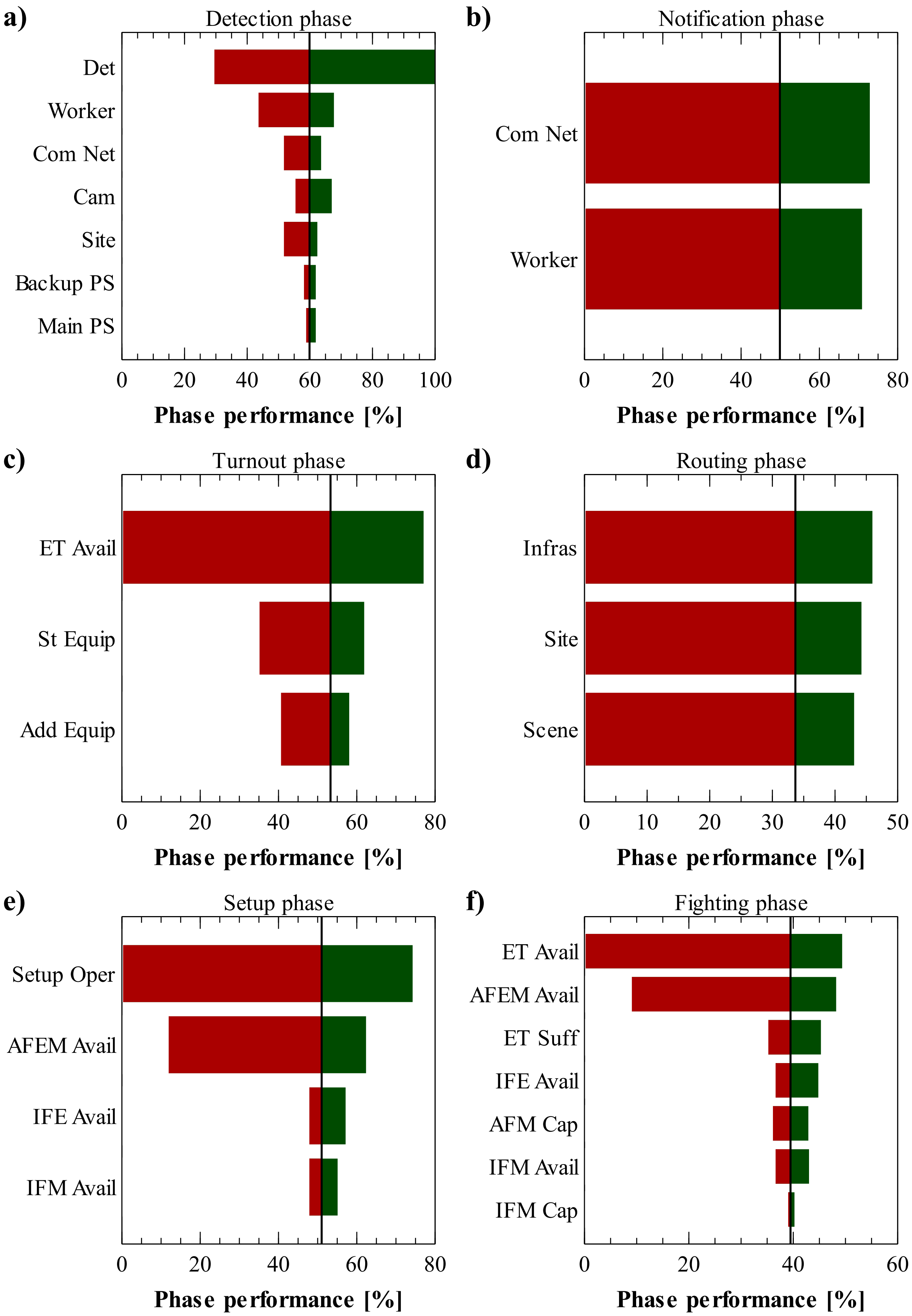

Figure 5.17. Sensitivity analysis of the performance of each phase to the factors' variation in the case of earthquake-induced accidents. See Table 5.2 for the definition of the factors.

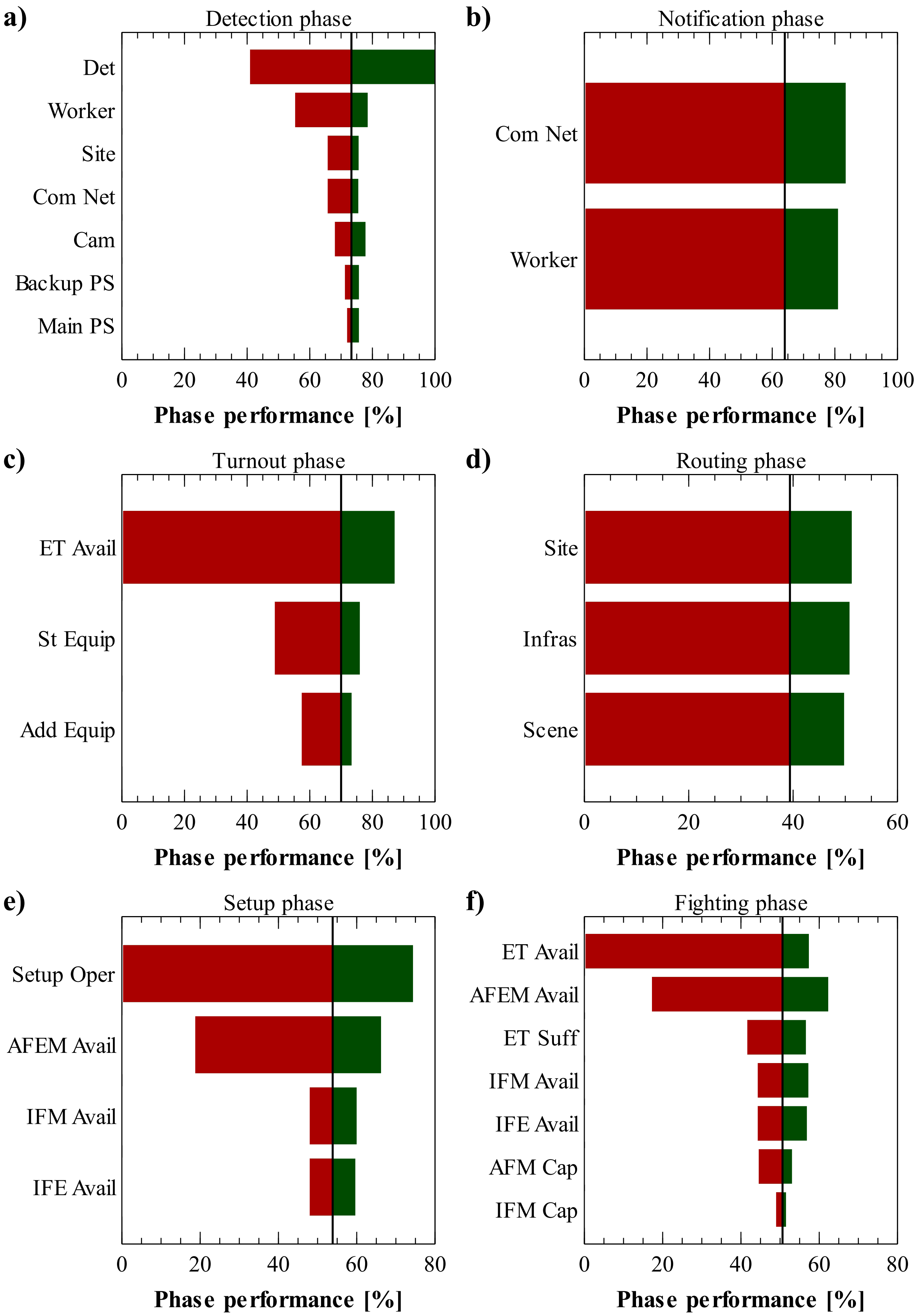

Figure 5.18. Sensitivity analysis of the performance of each phase to the factors' variation in the case of flood-induced accidents. See Table 5.2 for the definition of the factors.

Besides the analysis of each phase, the influence of the factors was evaluated also on the overall emergency response performance. The results are reported in Figure 5.19. Probabilities used in the calculations refer to the mean value obtained from the survey.

As can be observed, the ability to carry out the setup operation is the most critical factor for both earthquakes and floods. Thus, any improvement that allows performing the task similarly to the case of conventional accidents leads to an increase in emergency response performance. In addition, considering earthquake-induced accidents (panel a in Figure 5.19), the availability of emergency teams, the communication network and the worker availability have equal influence on the emergency response performance as the setup operations. Other important factors that shall be considered to improve the emergency response performance in the case of earthquakes are all related to the routing phase, specifically the accessibility of the scene, the external infrastructure, and the site. As for flood events, additional factors that should be accounted for the improvement of the emergency response performance together with the setup operation are the accessibility of the external infrastructure and the site, the communication network, and the worker availability. Eventually, although a reduced relevance is reported, the accessibility of the scene, the availability of emergency teams and the availability of additional firefighting equipment and material are worth a specific mention. Noteworthy, all the factors identified in Section 5.2.2 affects the emergency response performance. Nevertheless, the aim of this analysis was the identification of the more relevant ones.

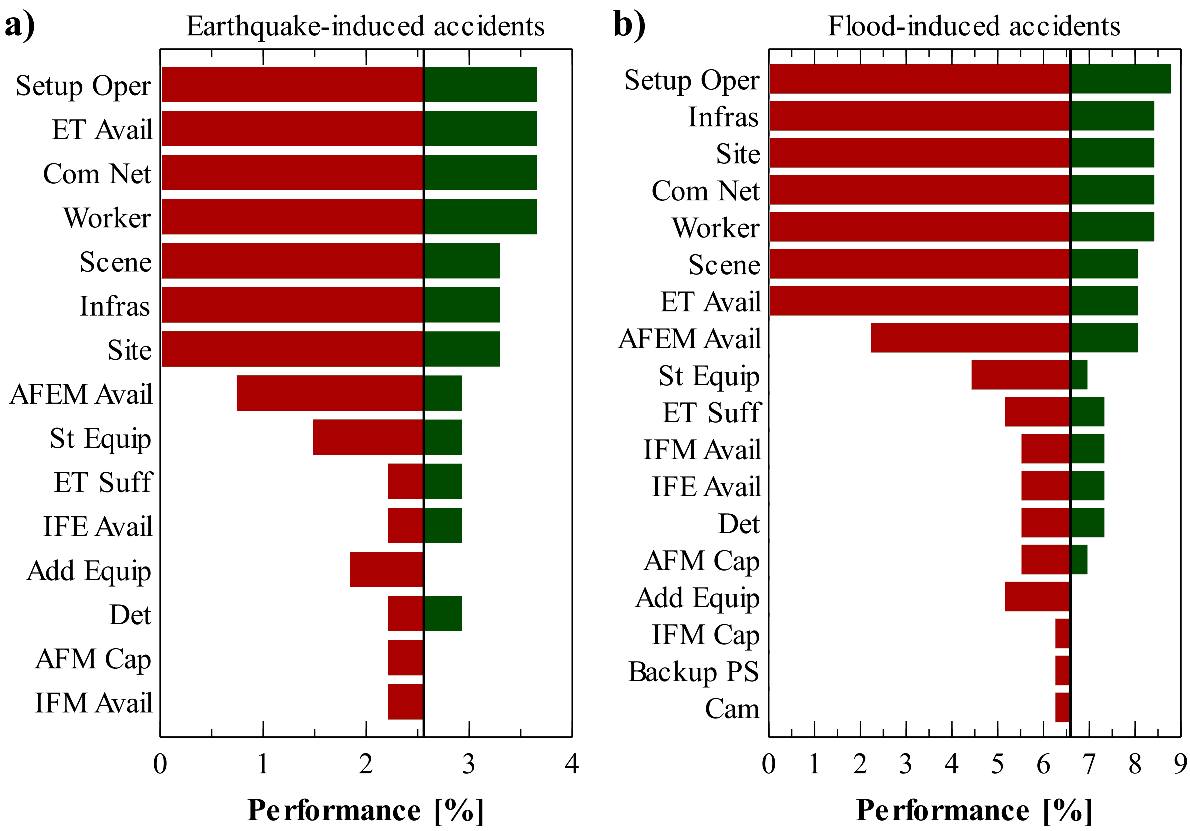

Figure 5.19. Sensitivity analysis of the performance of the entire emergency response process to the factors' variation for (a) earthquake-induced accidents and (b) flood-induced accidents. See Table 5.2 for the definition of the factors.

5.3.4 Analysis of the time required for emergency response

This section reports the results related to the emergency response time. The quantification of the time required was performed following the procedure described in Section 5.2.5. Four sets of repetitions were tested, specifically $1\cdot10^4$, $1\cdot10^5$, $1\cdot10^6$, and $1\cdot10^7$. Preliminary results are shown in Figure 5.20, where a comparison among the results obtained from the Monte Carlo simulation considering the four different numbers of repetitions is presented. As shown in the figure, a low accuracy is obtained when considering $1\cdot10^4$ repetitions, while similar results are obtained in the other cases. Thus, the results related to $1\cdot10^6$ repetitions were considered acceptable considering a trade-off between accuracy and computational cost [54–56].

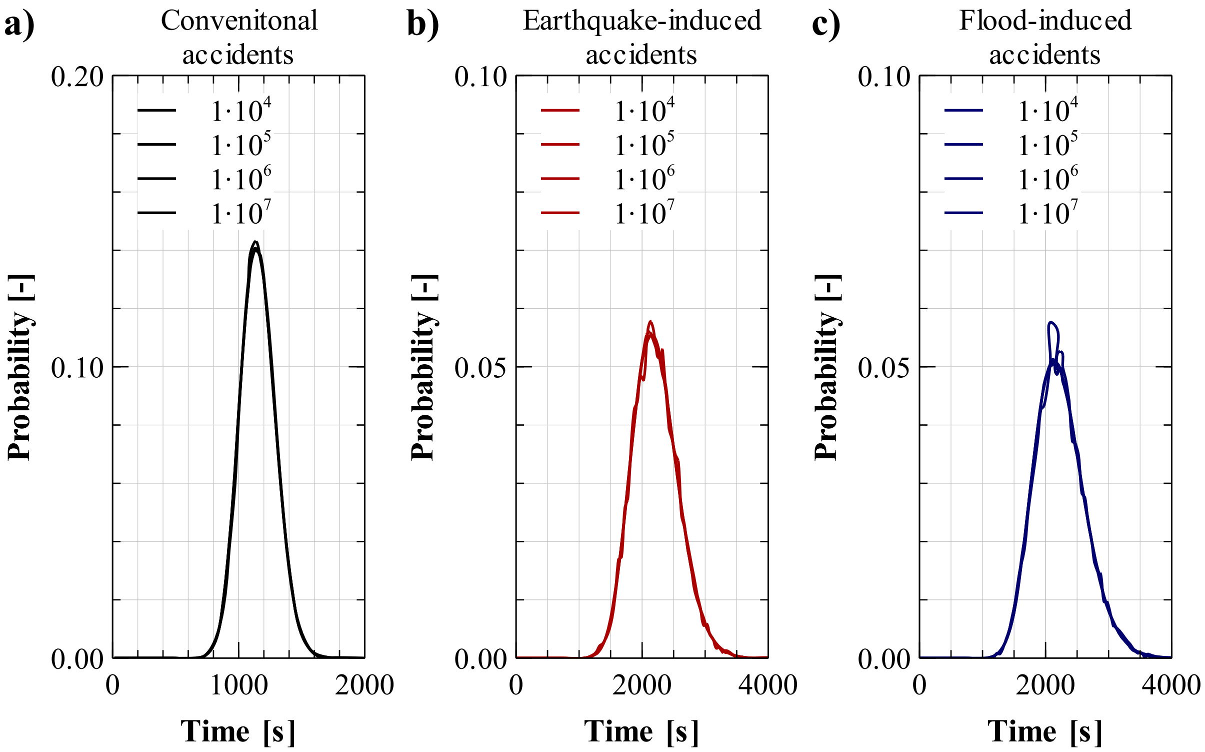

Figure 5.20. Comparison among the results obtained from the Monte Carlo simulation considering four different numbers of repetitions for (a) conventional accidents, (b) earthquake-induced accidents, and (c) flood-induced accidents.

The time required to complete each phase of the emergency response from the detection to the setup in the case of conventional accidents (grey), earthquake-induced accidents (red), and flood-induced accidents (blue) is reported in Figure 5.21. As can be observed, all the phases are strongly influenced in terms of time by the occurrence of natural events. In addition, the routing phase and the setup phase result to be the most affected ones. The observed trend is in line with the discussion reported in this study concerning the performance of the phase shown in Section 5.3.2.

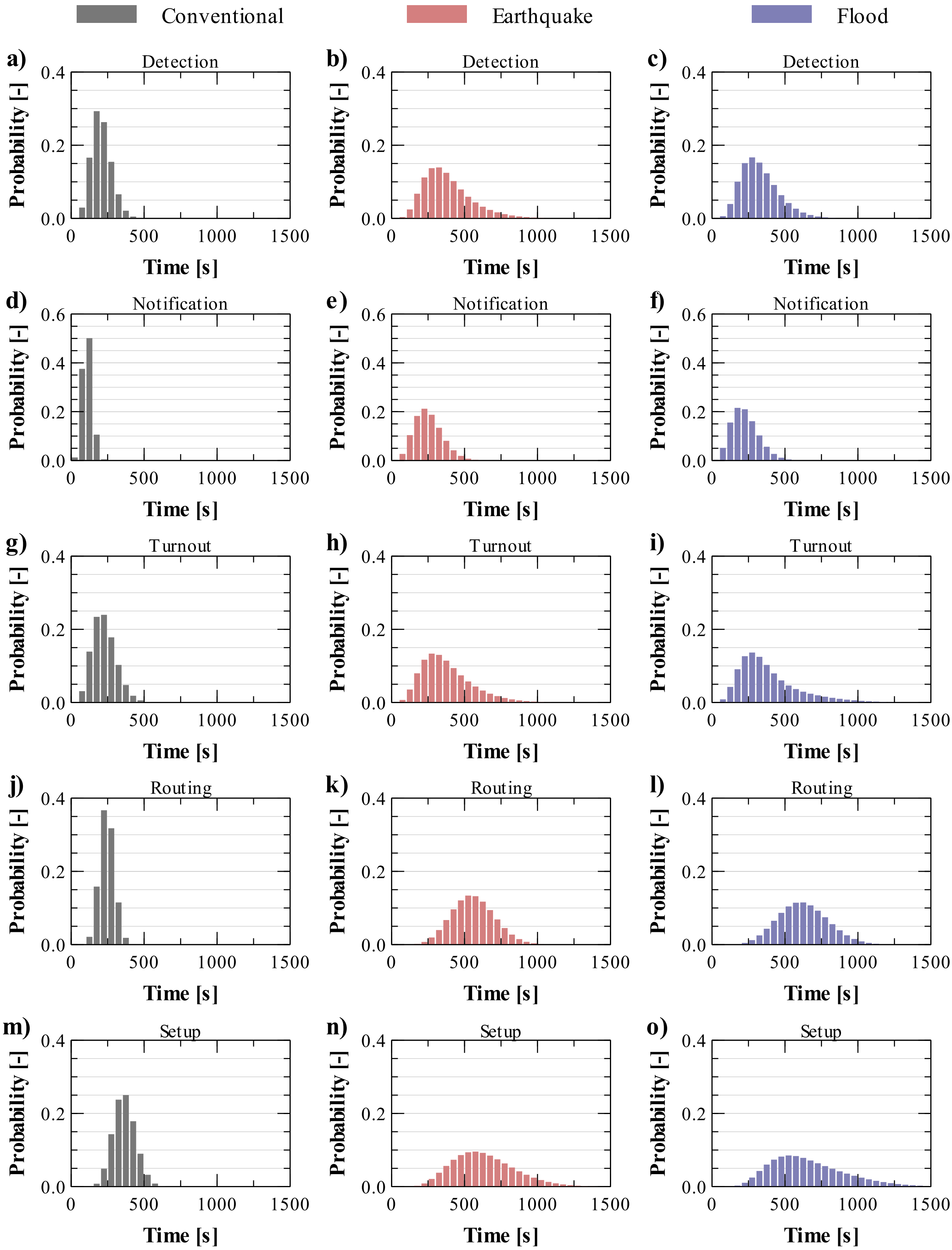

Figure 5.21. Time required to complete each phase of the emergency response from the detection to the setup in the case of conventional accidents (grey, panels a, d, g, j, and m), earthquake-induced accidents (red, panels b, e, h, k, and n), and flood-induced accidents (blue, panels c, f, i, l, and o).

Besides analysing each phase, it is very important to evaluate the overall emergency response time, which is reported in Figure 5.22. Comparing the results obtained for the three cases, substantial differences can be observed between the case of conventional accidents and that of Natech events, while a similar trend is obtained for earthquake-induced accidents and flood-induced accidents.

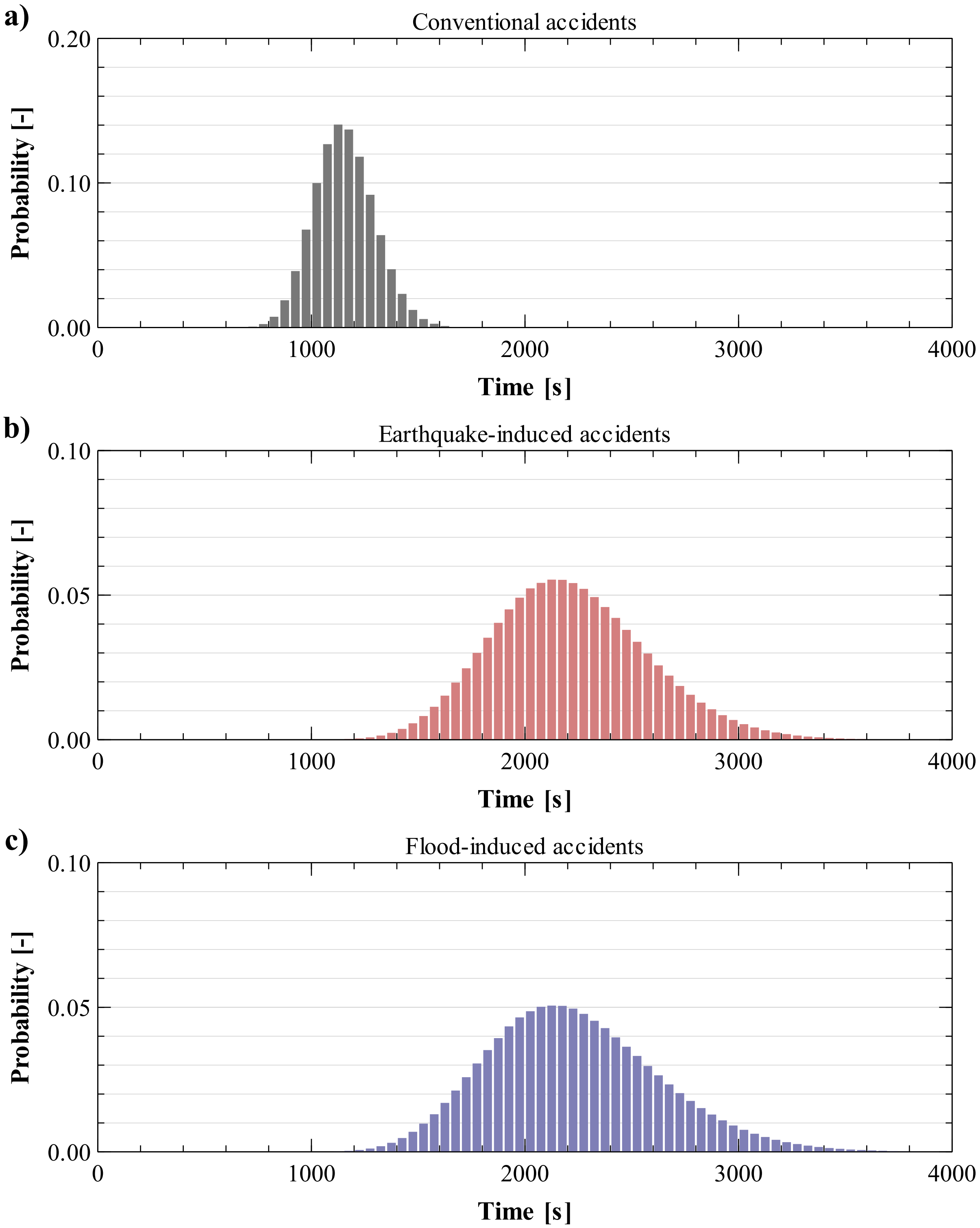

Figure 5.22. Time required to complete the emergency response in the case of (a) conventional accidents, (b) earthquake-induced accidents, and (c) flood-induced accidents.

According to Figure 5.22-a, the time required for the emergency response ranges from around 13 to 25 minutes in conventional accidents. These results are in line with the range proposed by Landucci et al. [11] in its upper value, while a more conservative value for the lower range is obtained in the present study. Eventually, the most probable time value in conventional accidents is around 19 minutes. As for earthquakes and floods (panels b and c, Figure 5.22), the time required ranges from around 20 to 60 minutes, and the most probable time value is around 35 minutes. Differently from the conventional case, this value is not centred in the range and suggests a distribution with larger probabilities at high time values. Overall, a delay factor of around 1.8 is obtained in the case of earthquakes and floods considering the most probable time value required to carry out the emergency response.

5.4 Conclusions

The emergency response is a paramount barrier used to ensure the safety of plants in the case of fire-driven cascading events. When these scenarios are caused by Natech accidents, the emergency response itself may also be affected by the occurrence of the natural disaster. Despite this, marginal attention was dedicated to the topic in the literature.

The present chapter aims at filling this gap by proposing a methodology for the evaluation of the emergency response performance and time in the case of natural events. The methodology makes use of a Bayesian Network model and a survey to quantify the performance of the emergency response. In addition, it allows the calculation of the time required to carry out the emergency response by means of a Monte Carlo simulation.

Results obtained from the application of the methodology identified the routing and the setup as the most affected phases of the emergency response. In addition, the methodology also identifies elements of the emergency response more affected by natural events. Results of the Monte Carlo simulation suggest that the time required to perform the emergency response in the case of earthquake and flood is almost double that in the case of conventional accidents.

Eventually, the results of the present chapter can be intended as an essential building block to provide a step forward for a more reliable quantitative risk assessment of Natech accidents. Hence, the emergency response performance obtained may be used to assess the probability of an effective intervention when quantifying the possible outcome in cascading events caused by natural events. Moreover, the methodology for the calculation of the emergency response time proposed in the present chapter represents a solid approach to quantifying the delay in the case of Natech accidents. This result may be used as suggested in Chapter 4 concerning the intervention time when calculating the failure probability of equipment items exposed to fire.

5.5 References

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Chapter 6:
CONCLUSIONS AND FUTURE DEVELOPMENTS

Natural disasters have always impacted human settlements, often causing severe consequences for the population. Severe natural disasters occurred in the last decades, such as earthquakes, floods, and hurricanes. These events affected several countries causing damage to human health and relevant economic losses. In addition, natural disasters also affected the industrial system and production processes, causing both short-term and long-term effects. Indeed, destructive interactions between natural events and industrial installations may result in technological scenarios, leading to the so-called Natech (natural disasters triggering technological scenarios) accidents. The occurrence of these accidents may worsen the consequences of the natural disasters. Moreover, natural events and disasters are expected to increase in frequency, further increasing the concern related to Natech accidents. In this framework, the results obtained in the present research project and reported in this thesis represents an advance in the study of Natech accidents, providing results and methods that allow for filling some of the gaps existing in the literature.

6.1 Conclusions

A comprehensive overview of Natech accidents was performed in the present thesis through the analysis of over 9000 records. As a result, an increasing trend over time of Natech accidents was observed, demonstrating the relevance of the issue. Meteorological events resulted to be the main trigger of Natech scenarios. Earthquakes, instead, represent the most catastrophic natural hazard in terms of damage to humans and assets. In addition, event trees were quantified for specific categories of substances. Moreover, probabilities of ignition for releases triggered by earthquakes, floods, and lightning were calculated. This information may support a more effective assessment of technological scenarios triggered by natural events.

The investigation of past Natech accidents also demonstrated that wildfires facing industrial installations may lead to technological accidents. In addition, climate change and global warming are promoting the conditions for wildfire development and rapid spread. For this reason, ensuring the safety of facilities exposed to wildfires is paramount. This is achieved providing a technically sound approach for the definition of safety distances that avoids the escalation of the fire inside the plant. The methodology proposed is a valuable tool since the early design stages of the plant, and it allows for the definition of the safety distances even in absence of detailed information. Moreover, it can be used as a preliminary screening of equipment items possibly affected by the wildfire when existing layouts are evaluated. A vulnerability ranking of targets may be identified through the methodology, allowing for better planning of the emergency response.

Safety distances between wild vegetation and industrial items cannot always be guaranteed. In this perspective, the assessment of the vulnerability of the plant to wildfire events is paramount. To this aim, an innovative methodology for the assessment of wildfire-induced primary Natech and related domino escalation events was developed. The methodology accounts for the specific behaviour and the intrinsic dynamic features of wildfire events and related cascading events, considering the synergistic effects of several simultaneous fires. The developed approaches can be coupled with those already existing in the literature for the quantification of the risk in the case of other natural events. The application of the methodology to a case study showed the importance of the intervention time in the assessment of the vulnerability, demonstrating the vital role of emergency response in the case of Natech accidents and related domino escalation.

The emergency response can be also affected by the occurrence of natural events. These effects should be considered dealing with the quantitative risk assessment of cascading events triggered by Natech accidents. To this aim, a methodology for the quantification of the emergency response performance and time was developed and applied to earthquakes and floods. In addition, the emergency response phases and elements most affected by natural events were identified.

Overall, the tools developed in the present thesis represent a step forward for the Quantitative Risk Assessment of Natech accidents. In addition, the proposed approaches provide a solid basis for the definition of effective strategies for risk mitigation and reduction. The implementation of the developed methodologies allows for the improvement of the resilience of industrial plants to natural hazards. A reliable evaluation of all these aspects is paramount, especially considering the effects that climate change has on the severity and frequency of such events.

6.2 Future developments

In perspective, further improvements of the developed methodologies may be foreseen. In particular, the methodology for the calculation of safety distances is developed considering only storage tanks as possible targets. These represent the most credible targets since they are typically located at the plant boundary. Nevertheless, broadening the methodology to other targets is important to ensure the safety of all industrial items possibly affected by wildfire. In addition, safety distances are defined considering thermal radiation from wildfire, thus protecting tanks also from flame impingement. Nevertheless, firebrands may travel long distances. Thus, introducing them as a source of hazard may extend the methodology.

These aspects represent also a step forward in the vulnerability assessment of industrial sites to wildfires. The vulnerability of the plant is evaluated by considering fires as drivers of escalation. Other escalation vectors may be identified, such as missile projections. Thus, in perspective, tailoring the methodology to accommodate the possibility of including other impact vectors may allow for a more complete assessment of the vulnerability.

Eventually, emergency response performance was quantified for earthquakes and floods. Nevertheless, the methodology is general, and it can be applied to any natural event, such as wildfires. In addition, results may be included in the existing methodologies for the Quantitative Risk Assessment of Natech accidents. Indeed, emergency intervention is typically considered a procedural barrier in the assessment of domino escalation scenarios. Thus, the modification of the risk due to the effects of natural events on the emergency response may be evaluated, allowing a more reliable quantification of the risk.

NOMENCLATURE

Chapter 2
A COMPREHENSIVE ANALYSIS OF NATECH ACCIDENTS
IN THE CHEMICAL AND PROCESS INDUSTRY 25

Acronym	Definition
Clima	Climatological events
E	Explosion
EC	Environmental contamination
F	Fire
FF	Flash fire
Geo	Geophysical events
Hydro	Hydrological events
Meteo	Meteorological events
MS	Multiple scenario
R-NFC	Release with no further consequences
TGD	Toxic gas dispersion
VCE	Vapor cloud explosion

Chapter 3
SAFETY DISTANCES TO PREVENT NATECH ACCIDENTS
DUE TO WILDFIRE EVENTS IN THE WILDLAND-INDUSTRIAL INTERFACE 73

Symbol	Definition	Unit of measure
D	Distance between fire and target	m
D_w	Distance between wall and target	m
E	Emissive power	$W \cdot m^{-2}$
F	View factor between fire and target	-
F_m	Mitigated view factor between fire and target	-
$F_{w \to t}$	View factor between wall and target	-
H_v	Height of the vegetation (trees)	m
H_w	Height of the wall	m
I	Thermal radiation on target surface	$W \cdot m^{-2}$
I_m	Mitigated thermal radiation on target surface	$W \cdot m^{-2}$
I_B	Byram's fireline intensity	$W \cdot m^{-1}$
L_f	Flame length	m
RT	Reference time	s
t_e	Exposure time to wildfire	s
T_f	Flame temperature	K
t_r	Response time of emergency teams	s
ttf	Time to failure	s
V	Volume of the tank	m^3
W_f	Fire front width	m
ε_f	Flame emissivity	-
η	Radiation intensity reduction parameter	-

σ	Stefan-Boltzmann constant (5.67·10-8)	$W \cdot m^{-2} \cdot K^{-4}$
θ	Flame tilt angle	rad
τ_a	Atmospheric transmissivity	-

Acronym	**Definition**
CF	Crown fire
GF	Grassland fire
SF	Shrubland fire

Chapter 4
VULNERABILITY ASSESSMENT OF NATECH AND DOMINO SCENARIOS TRIGGERED BY WILDFIRES IN INDUSTRIAL PLANT 115

Symbol	**Definition**	**Unit of measure**
a	Coefficient used in the EV evaluation	-
A	Probit coefficient	-
B	Probit coefficient	-
C_i	Consequences of the *i-th* target	-
C_q	Consequences of the *q-th* combined scenario	-
D	Distance between fire and target	m
E_{wf}	Emissive power of the wildfire	$W \cdot m^{-2}$
f	Simple frequency	y^{-1}
f_{wf}	Wildfire frequency	y^{-1}
$F_{wf \to i}$	View factor between wildfire and the *i-th* target	-
H_v	Height of the vegetation (trees)	m
$IR_{j \to i}$	Thermal radiation from the *j-th* tank to the *i-th* target	$W \cdot m^{-2}$
$IR_{wf \to i}$	Thermal radiation from wildfire to the *i-th* target	$W \cdot m^{-2}$
I_i	Impact vector on the *i-th* target	$W \cdot m^{-2}$
L_f	Flame length	m
N	Number of fatalities	-
P_{fail}	Failure probability	-
P	Probability of the combined scenario	-
TD_i	Thermal dose received by the *i-th* target	$J \cdot m^{-2}$
$TD_{C,i}$	Critical thermal dose of the *i-th* target	$J \cdot m^{-2}$
t	Time	s
ttf_i	Time to failure of the *i-th* target	s
V	Volume of the tank	m^3
W_f	Fire front width	m
Y	Probit variable	-
α	Coefficient in TD calculation	-
δ_i	Coefficient used to account the *i-th* target in the calculation	-
θ	Flame tilt angle	rad
τ_a	Atmospheric transmissivity	-

Acronym	**Definition**
CF	Crown fire
GF	Grassland fire
LSIR	Local-Specific Individual Risk

PLL	Potential life loss
QRA	Quantitative risk assessment
S	Status vector
SF	Shrubland fire
SG	Scenario Generation
T	List of targets
TD	Thermal dose vector

Chapter 5
EMERGENCY RESPONSE IN CASCADING SEQUENCES
TRIGGERED BY NATURAL EVENTS 151

Symbol	**Definition**	**Unit of measure**
d	Delay factor in the case of natural events	-
$delay_{range}$	Range provided in the survey for the delay factor in the case of natural events (NE)	-
max_{range}	Maximum value of the time range provided in the survey to complete a phase (PH)	s
min_{range}	Minimum value of the time range provided in the survey to complete a phase (PH)	s
mpv	Most probable time value provided in the survey to complete a phase (PH)	s
P_{fail}	Probability of the "*fail*" status for technical needs (TN)	-
P_{work}	Probability of the "*work*" status for technical needs (TN)	-
$P_{sufficient}$	Probability of the "*sufficient*" status for technical needs (EN)	-
$P_{not\ sufficient}$	Probability of the "*not sufficient*" status for technical needs (EN)	-
$P_{standard}$	Probability of the "*standard*" status for response activities (RA)	-
$P_{delayed}$	Probability of the "*delayed*" status for response activities (RA)	-
P_{no}	Probability of the "*no*" status for response activities (RA)	-
$P_{survey,\ standard}$	Probability of the "*standard*" status according to the survey answer for response activities (RA)	-
$P_{survey,\ delayed}$	Probability of the "*delayed*" status according to the survey answer for response activities (RA)	-
$P_{survey,\ no}$	Probability of the "*no*" status according to the survey answer for response activities (RA)	-
$P_{success}$	Probability of the "*success*" status for phases (PH) and emergency response	-
$P_{failure}$	Probability of the "*failure*" status for phases (PH) and emergency response	-
$P_{success}(PH\|delay)$	Probability of successfully completing the phase (PH) given a delay in it	-
$P_{failure}(PH\|delay)$	Probability of not completing the phase (PH) given a delay in it	-
Performance(PH,NE)	Performance of the phase PH in the case of the natural event NE	-
Performance(ER,NE)	Performance of the emergency response in the case of the natural event NE	-
Pa (X_i)	Parent nodes of X_i	-
r	Numeric value that accounts for the probability of delay in the case of natural events	-
t_{CA}	Time required in conventional accidents	s
t_{NE}	Time required in the case of natural events	s

μ	Mean of the normal distribution	s
σ	Standard deviation	s

Acronym	**Definition**
Add. Equip.	Additional/specific equipment availability
AFEM Avail.	Additional firefighting equipment and material availability
AFM Cap.	Additional firefighting material capacity
Backup PS	Backup power supply
CA	Conventional accidents
Cam	Cameras
Com. Net.	Communication network
CPT	Conditional probability table
D	Delay
DAG	Directed acyclic graph
Det	Detectors
EN	Extensive need
ER	Emergency response
ET Avail.	Emergency team availability
ET Num.	Emergency team number
F	Fail
IFE Avail.	Internal firefighting equipment availability
IFM Avail.	Internal firefighting material availability
IFM Cap.	Internal firefighting material capacity
Infras.	External infrastructures accessibility
Main PS	Main power supply
MCS	Monte Carlo Simulation
N	No
NE	Natural events
NF	Not sufficient
PH	Phase
Q1	First quartile
Q3	Third quartile
RA	Response activity
RES	Responders
S	Standard
Scene	Accident scene accessibility
Setup Oper.	Setup operation
Site	Industrial site accessibility
St. Equip.	Standard equipment suitability
SUF	Sufficient
TN	Technical need
W	Work
Worker	Worker availability

LIST OF FIGURES

LIST OF TABLES

LIST OF PUBLICATIONS

Document	Article
Authors	Casson Moreno V., Ricci F., Sorichetti R., Misuri A., Cozzani V.
Title	Analysis of past accidents triggered by natural events in the chemical and process industry
Year	2019
Source	Chemical Engineering Transactions, Volume 74, Pages 1405-1410
Abstract	NaTech events (Natural Hazard Triggering Technological Disasters) are becoming an increasing concern in the Chemical and Process Industry (CPI). From a risk management standpoint, a better understanding of such events is of paramount importance. In this perspective, the analysis of past accidents is crucial, being almost the only source of information on the possible interactions between natural threats and CPI. To this aim, the present work collected 438 past NaTechs that affected CPI, analysing the trends of accidents with respect to the trend of natural disasters, the geographical localization, the type of natural hazard triggering the accident, the final scenarios (e.g. fire, explosion, …) and the consequences on human and assets. For each type of NaTech, significant accidents have been reported and discussed.

Document	Article
Authors	Ricci F., Casson Moreno V., Cozzani V.
Title	Analysis of Natech accidents triggered by extreme temperatures in the chemical and process industry
Year	2020
Source	Chemical Engineering Transactions, Volume 82, Pages 79-84
Abstract	The increase both in frequency and magnitude of natural events makes the study of the interaction between natural events and industrial facilities of paramount importance. Natural events may affect facilities leading to major accidents (e.g. explosion, fire, …) and these events are called NaTech (natural hazards triggering technological disasters). Extreme temperatures are one of the causes of NaTechs and the first step in studying their interaction with industrial facilities is given by the historical analysis of past accidents, being essentially the only source of information. To do this, a dataset of 305 past events was collected and analysed in order to highlight the main features of these accidents, such as the trend over the years, the geographical location, the final scenarios and the type of industrial sectors involved.

Document	Article
Authors	Ricci F., Scarponi G.E., Pastor E., Planas E., Cozzani V.
Title	Safety distances for storage tanks to prevent fire damage in Wildland-Industrial Interface
Year	2021
Source	Process Safety and Environmental Protection, Open Access, Volume 147, Pages 693-702
Abstract	Wildfire occurrence frequency is increasing worldwide, generating more and more concern, especially in Wildland-Urban interfaces (WUI) and Wildland-Industrial Interfaces (WII) areas. Wildfires approaching WII can cause severe damage to people and industrial assets. In these scenarios, storage tanks present in industrial installations are among the most vulnerable pieces of equipment, since they are usually located in the proximity of the plant boundary. If hazardous substances are stored, tank damage caused by the fire can lead to loss of containment and trigger technological accident scenarios, escalating the consequences. Preserving the integrity of this type of equipment in case of wildfires is of paramount importance. The present study proposes a stepwise methodology for the evaluation of safety distances between storage tanks and vegetation that may be affected

by a wildfire. According to the available data on the wildfire, on the lay-out and on the tanks that are likely to be affected, the methodology provides safety distances that may be applied to design fuel-reduced fringes around the industrial facility. The methodology proposed represents a quantitative tool for the calculation of safety distances that can guide industrial managers and assist regulators in the definition of more reliable standards. The comparison of the safety distances resulting from the present study with regulations and guidelines currently in use in different countries rises concern about the possible underestimation of required safety distances in the case of severe wildfires.

Document	Article
Authors	Ricci F., Casson Moreno V., Cozzani V.
Title	A comprehensive analysis of the occurrence of Natech events in the process industry
Year	2021
Source	Process Safety and Environmental Protection, Volume 147, Pages 703-713
Abstract	Natural events triggering technological scenarios (Natech events) are an increasing concern for regulatory authorities and industry, in particular in areas prone to natural disasters. A comprehensive analysis of the occurrence of Natech scenarios affecting the process industry is presented. A dataset of 9100 past accidents that took place in the last 70 years was compiled and analysed, with the aim of understanding the trend of Natech events, their geographical distribution, the final technological scenarios, and the associated consequences in terms of human losses and asset damages. Meteorological events, such as storms, extreme temperatures and lightning were found to be the main trigger of Natech scenarios (86 %). Despite the difficulty in collecting homogeneous data worldwide, an increasing number of Natech events over the time is observed. Moreover, specific increases in the occurrence of Natech events correspond to the occurrence of severe natural disasters as the devastating hurricanes that affected the Gulf of Mexico in recent years. The societal risk curve associated to Natechs was calculated, evidencing the relevance of extremely severe accidents (> 100 deaths). The analysis of the dataset also allowed building quantified event trees for the evolution of Natech scenarios. Specific ignition probability values for Natech events were estimated.

Document	Article
Authors	Ricci F., Scarponi G.E., Pastor E., Muñoz J.A., Planas E., Cozzani V.
Title	Vulnerability of industrial storage tanks to wildfire: A case study
Year	2021
Source	Chemical Engineering Transactions, Volume 86, Pages 235-240
Abstract	Wildfires approaching the Wildland-Industrial Interfaces can be a serious threat for industrial items located at the plant boundary. These items are typically storage tanks involving large amounts of hazardous substances. Ensuring their integrity is of paramount importance to prevent the wildfire spread inside the industrial plant, avoiding the occurrence of major accidents such as fires, explosions and toxic releases. A methodology for the evaluation of safety distances between tanks and vegetation for the protection from wildfire hazard was developed and applied to a case study. The outcomes provide useful information for an effective emergency response planning in the case of wildfire. Moreover, the results obtained rise concern about the appropriateness of clearance areas between the vegetation and industrial areas currently adopted.

Document Article
Authors Ricci F., Scarponi G.E., Pastor E., Planas E., Cozzani V.
Title Asset Integrity in the Case of Wildfires at Wildland-Industrial Interfaces
Year 2022
Source Chemical Engineering Transactions, Volume 90, Pages 247-252
Abstract Wildfires are uncontrolled fires involving the combustion of wild vegetation. When a wildfire front approaches the Wildland-Industrial Interface there can be a serious threat for process and storage equipment items located at the plant boundary. Ensuring the integrity of such equipment prevents the fire from spreading inside the plant site and causing major accidents such as fire, explosion, and toxic gas dispersion. The provision of adequate clearance areas is paramount since the early stages of the plant design. Once the facility is built, the implementation of safety measures can protect industrial items and ensure tank integrity. A tailored methodology for the calculation of safety distances between wild vegetation and tanks accounting for the safety system was developed and applied to a case study. The outcomes provide useful information on the effectiveness of safety measures for the protection of industrial items exposed to wildfire.

Document Article
Authors Ricci F., Bonvicini S., Casson Moreno V., Cozzani V.
Title The Quantitative Assessment of Damage to the Environment in Major Accidents Caused by Natural Events
Year 2022
Source Chemical Engineering Transactions, Volume 90, Pages 253-258
Abstract The release of hazardous materials induced by natural events affecting industrial facilities presents peculiar characteristics because of the huge potential extension of the affected areas. The reduction of both the likelihood and the magnitude of such events represents an essential step to reduce the risk associated with Natech accidents. Nevertheless, the evaluation of damage to the environment in Natech events has been poorly addressed. In the present study, past accidents analysis was carried out, using both a detailed description of specific accidents and an extended database of Natech events. Lessons learnt as well as possible common patterns and main features related to such accidents were identified and discussed. The results of the present study can be intended as a preliminary step for the development of models for the quantitative assessment of damage to the environment in major accidents caused by natural events.

Document Article
Authors Ricci F., Yang M., Reniers G., Cozzani V.
Title The Role of Emergency Response in Risk Management of Cascading Events Caused by Natech Accidents
Year 2022
Source Chemical Engineering Transactions, Volume 91, Pages 361-366
Abstract 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.

Document Book chapter
Authors Ricci F., Scarponi G.E., Landucci G., Cozzani V.
Title Chapter Three - Fire driven domino effect
Year 2021
Source Methods in Chemical Process Safety, Volume 5, 2021, Pages 71-117
Abstract Fire is the more frequent cause of domino effects. Escalation scenarios triggered by fires are among the more severe accident scenarios experienced in the chemical and process industry. The present chapter addresses the fundamental phenomena that may lead to the failure of atmospheric and pressurized equipment items, when exposed to intense heat flows caused by industrial fire scenarios. Simplified tools and detailed models for the assessment of the time to failure of equipment involved in fire are presented, and the limitation in both approaches are discussed. Correlations for the straightforward calculation of the time to failure and threshold values of radiation below which domino effect should be considered unlikely are reported and discussed. Finally, an inherent safety approach based on safety distances for equipment damage addressing the prevention of domino effect triggered by fire is presented.

Document Proceedings
Authors Cozzani V., Misuri A., Ricci F., Caratozzolo V., Salzano E.
Title Gestione del Rischio Natech: il ruolo dei sistemi di sicurezza
Year 2021
Source Atti di convengno. Sicurezza e Affidabilità delle attrezzature a pressione. Pages 703-711

Document Proceedings
Authors Ricci F., Yang M., Reniers G., Cozzani V.
Title Emergency Response Management in the Risk Assessment of Cascading Events caused by Natech Accidents
Year 2022
Source Proceedings of GRICU 2022. Pages