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Emergency response in cascading scenarios triggered by natural events

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ABSTRACT

Emergency response is a procedural safety barrier of paramount importance for the mitigation of fire scenarios and the prevention of escalation. However, in Natech scenarios, emergency response may be affected by the natural event impacting the site. Indeed, when contrasting Natech accidents, emergency responders have to face both the natural event and the cascading technological scenario. Despite the criticality of the issue, limited attention was devoted to date to the analysis of emergency response in cascading sequences triggered by natural events. The present study provides a novel and technically sound methodology to assess the performance of emergency response and the required intervention time in Natech scenarios. An expert survey combined with a Bayesian Network model was used to assess the performance of the emergency response. The routing and setup phases were identified as those mostly affected by natural events. Monte Carlo simulations were used to obtain baseline data and specific probability distributions for the time required to carry out the emergency response considering the factors that may hinder the response during natural events. In Natech accidents, the time for effective mitigation resulted higher of at least a factor 2 with respect to that expected in the case of conventional accidents. The methodology developed may be used to support the improvement of the emergency management of Natech scenarios, allowing for a detailed definition of site-specific emergency response plans. Moreover, the results may be used to provide a more accurate assessment of the fire-driven escalation probability in Natech events.

1. Introduction

Natural disasters are a worldwide concern, potentially affecting any area of the world and causing severe consequences for the population [1]. Interactions between natural disasters and industrial activities where relevant quantities of hazardous substances are handled may result in cascading technological scenarios, worsening the consequences of natural disasters. Accidents caused by natural hazards are referred to as Natech (natural hazards triggering technological accidents) events [2,3]. The awareness of the potential hazards caused by these events has considerably grown in the last decades [4–7]. On the one hand, the number of reported intense natural events is increasing [8], as well as the number of Natech accidents [9]. On the other hand, the occurrence of several Natech accidents [10–12] not only demonstrated that natural events can trigger technological scenarios, but also that the consequences can be extremely severe [13–15]. Moreover, Natech accidents may be characterized by multiple simultaneous failures [16–19] and natural disasters may affect utility systems, safety systems, and lifelines [16,18,20]. Both these aspects concur to trigger cascading sequences in Natech scenarios [11,13,18,21].

Cascading scenarios are events where an accident from a primary unit escalates, often propagating to other adjacent equipment items, resulting in further damages to the plant and significantly higher impacts [22–25] than those caused by the primary scenario. The primary scenario initiates the cascading sequence due to an escalation vector generated by its physical effects, which may affect other (secondary) equipment items. One or more secondary scenarios may occur simultaneously or in sequence (e.g., fire, explosion, toxic dispersion) [26,27]. Fires and explosions are the primary scenarios that more frequently generate cascading sequences [28,29]. Fires have been the main cause of cascading events in the last fifty years and cascading events triggered by fire resulted in extremely severe accidents in the chemical and process industry [28–31].

Escalation due to fires may derive from full engulfment, partial

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Table 1
Phases of emergency response considered in the present study.

Phase	Definition and main features
Detection	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.
Notification	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).
Turnout	Begins when the accident is notified 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.
Routing	Starts when the emergency teams leave the fire station and ends when 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.
Setup	Begins once the emergency teams arrive at the accident scene and ends when they start fighting the fire. Within the phase, the personnel establishes the water supply, sets up the necessary equipment, and performs all the needs to start the firefighting strategy.
Fighting	Starts when emergency teams begin to counteract the fire (firefighting, protecting neighboring tanks, etc.) and ends when the fire is completely extinguished.

impingement, or distant source radiation [32,33]. In cascading sequences caused by fires, a time-lapse occurs between the start of primary and secondary events. Indeed, time is needed to raise the temperatures of the shell and of the internal fluid of target vessels to a value that compromises the structural integrity of the target items [32,33]. In the case of other escalation vectors different from fire (e.g., overpressure, fragments), the secondary scenarios are almost simultaneous with the primary event [34–38]. Hence, the emergency response is specifically relevant to avoid the occurrence of fire-driven cascading events. In addition, emergency team intervention is considered one of the more effective barriers in fighting the fire and preventing its spread to other equipment [28,29].

The role of emergency response in the framework of risk assessment and management is paramount [39,40]. The intervention of emergency teams is aimed at protecting human lives, the environment, and/or assets [41]. Ensuring the safety of assets is crucial to avoid the development of cascading sequences, limiting the consequences of the accident [29]. The emergency response becomes even more critical when dealing with Natech accidents since the probability of cascading events is higher than in conventional scenarios [11,13,18]. Actually, natural events may hinder and delay the emergency response, overloading the emergency system that has to contrast the consequences of natural and technological disasters simultaneously [18,42–44]. Indeed, the natural event is likely to hit a wider area than that of the industrial site, including nearby zones where people, buildings, and infrastructure may be present. This may also limit the availability of emergency teams and the effectiveness of the response [11,13,16,19]. In addition, technical barriers and equipment useful to prevent and mitigate technological accidents may be damaged by the natural event, becoming unavailable [21,45].

Despite the relevance of the issue, limited attention is devoted in the literature to the study of the emergency response in Natech accidents. Although several studies related to emergency response are available [46–49], most of them only consider fire-driven cascading events caused by conventional accidents without a specific focus on Natech scenarios. Beside considering only cascading events triggered by conventional scenarios, previous studies mostly investigate the effects of emergency response in determining the possibility and probability of domino effects, not specifically addressing the assessment of the performance of the emergency response in cascading scenarios [29,50–52]. A pioneering study focusing on the emergency response in Natech scenarios was carried out by Bernier et al. [53], addressing the site accessibility during storm surge events. However, the study does not take into account other critical aspects that may arise during a natural event. Baser and Behnam [54] pointed out the need for a detailed and specific emergency response plan for cascading post-earthquake fires, addressing the criticalities related to the emergency response during seismic events such as the inability to extinguish multiple fires. Nevertheless, their study focused on the assessment of cascading sequence probability rather than on the evaluation of the emergency response performance.

The present study aims to develop an innovative approach to the assessment of emergency response performance in cascading events triggered by natural events. The innovative framework developed allows for an in-depth analysis of the time required to successfully display the emergency response during or after intense natural events as floods or earthquakes. It accounts for both the possible impairment of emergency responders and the unavailability of technical needs required to effectively perform the response caused by the natural event. The methodology developed in the present study also allows improving emergency management in chemical and energy facilities, supporting the definition of detailed and site-specific emergency response plans for Natech scenarios. In addition, the methodology can be integrated into quantitative risk assessment frameworks to support the quantitative assessment of escalation triggered by fire in Natech scenarios.

The innovative methodology developed in the present study is described in Section 2. Results concerning the quantitative assessment of emergency response for cascading sequences caused by earthquakes and floods are reported in Section 3. A discussion of the results is provided in Section 4, while some conclusions are drawn in Section 5.

2. Methodology

The evaluation of emergency response performance and intervention time in the case of natural events is paramount to carry out a reliable assessment of the risk in the case of cascading sequences triggered by Natech accidents. To this aim, a methodology for the quantification of performance modification in the case of fire-induced cascading sequence triggered by Natech accidents was developed in the present study. The methodology provides an innovative approach to the performance assessment of the emergency response in fire-induced cascading sequences, taking into account the requirements of the emergency response (tasks, human action, technical needs) and their possible unavailability or reduced effectiveness during natural events. A detailed assessment of the site-specific time required to display the emergency response during complex scenarios leading to cascading events is provided, addressing possible delays caused by the consequences of intense natural events. The is based on the definition of the phases of the emergency response (Step 0). Then, the assessment of the performance of emergency response is carried out by four sequential steps:

1. The definition of emergency response factors in each phase;
2. The characterization of baseline factors;
3. The assessment of the emergency response performance;
4. The assessment of the time required for emergency response.

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

2.1. Step 0: definition of the phases of emergency response

The emergency response can be schematized as a sequence of consecutive actions, each of which should be completed to effectively carry out the following phases and to complete the procedure [29,48–50]. In the present study, emergency response is divided in 6 main phases, based on the approaches proposed by Flynn [41] and by the U.S.

Table 2
Baseline factors considered for emergency response performance. The definitions of the factors are reported in Table A1 of the Supplementary Material.

Group	Factor	Acronym	States
Technical needs (TN)	Detectors	Det	Work, Fail
	Cameras	Cam	
	Main power supply	Main PS	
	Backup power supply	Backup PS	
	Standard equipment suitability	St Equip	
	Internal firefighting equipment availability	IFE Avail	
	Internal firefighting material availability	IFM Avail	
Response activities (RA)	Additional firefighting equipment and material availability	AFEM Avail	Standard, Delayed, No
	Worker availability	Worker	
	Communication network	Com Net	
	Industrial site accessibility	Site	
	Emergency team availability	ET Avail	
	Additional/specific equipment availability	Add Equip	
	External infrastructures accessibility	Infras	
	Accident scene accessibility	Scene	
	Setup operation	Setup Oper	
Extensive needs (EN)	Internal firefighting material capacity	IFM Cap	Sufficient, Not sufficient
	Additional firefighting material capacity	AFM Cap	
	Emergency team number	ET Num	

Fire Administration and the National Fire Data Center [55]. Table 1 reports the definition and main features of the six phases of emergency response considered.

The status of each of the above-defined emergency response phases needs then to be characterized. In the present approach, three states were considered for the representation of each phase:

- **Standard**. The "*standard*" status means that the phase can be concluded in standard times, thus without impediments and/or criticalities in its development.
- **Delay**. The "*delay*" status refers to the case in which the phase can be concluded with some delay with respect to standard conditions, 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.

2.2. Step 1: definition of emergency response factors

Each phase of the emergency response requires the completion of a complex sequence of activities exploiting specific technical equipment. To perform a detailed assessment of each action carried out by the emergency responders, the equipment required to carry out the activities, as well as other technical needs present on site that contribute to the emergency response (e.g., fire detectors, fire monitors, etc.) should be considered in the analysis. All these elements are called factors in the following.

In Step 1 of the methodology, the factors that may be affected by the occurrence of natural events were identified. The identification of the relevant emergency response factors was carried out reviewing the relevant technical literature and specific publications [56–60]. The preliminary list of factors obtained was validated considering the analysis of some cornerstone Natech accidents reported in the literature. In particular, Lindell and Perry [43] 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.
- 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 scenario, further worsening the identified criticalities [43].

Some of the criticalities identified by Lindell and Perry [43] have also occurred in other major Natech events. Ricci et al. [44] analyzed the aspects related to emergency response in accidents triggered by the Kocaeli earthquake and by the Great East Japan earthquake and tsunami. In addition to the issues reported by Lindell and Perry [43], other shortcomings were identified, such as:

- The inadequate design of mitigation safety systems.
- The shortage of fire-fighting materials to tackle multiple and simultaneous fires.
- The inappropriate emergency response plans for Natech accidents and related cascading events.
- Difficulties in the accessibility of external infrastructure needed to grant access to the plant.

In addition, some literature studies confirm that active and passive barriers are also relevant to emergency response, e.g. as detectors, may be affected by natural events [45,61,62].

Finally, the completeness and general value of the baseline list of factors identified was validated by specific interviews with experts in the field. A total of 3 interviews were carried out involving firefighters and company safety managers.

Table 2 reports the validated list of emergency factors obtained from the procedure outlined above and considered in the present study. A total of 19 factors relevant to the evaluation of emergency response performance in the framework of cascading events caused by Natech accidents were identified. A detailed definition of each factor is provided in the Supplementary Material.

Clearly enough, the list in Table 2 only includes baseline factors having a general relevance. When the detailed analysis of a specific site is of interest, the baseline list may be integrated with site-specific local factors using the available experience on past accidents, checklists, and interviews to personnel.

The 19 baseline factors identified were divided into 3 groups considering their different features:

- ***Technical needs*** (TN). This group contains all the physical equipment items necessary to carry out the emergency response

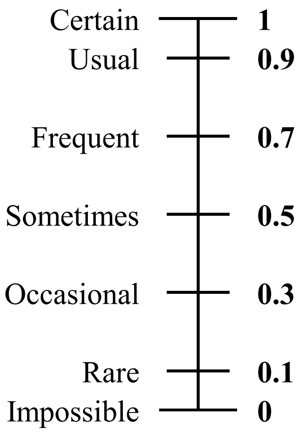

Fig. 1. The verbal scale adopted in the survey and the quantitative translation used in the analysis of the answers. Adapted from Vagias [68].

procedure. Only physical elements are present in this group, thus their possible states may be considered as "*work*" and "*fail*".

- ***Response activities*** (RA). This group includes all the elements/tasks of the emergency response that require a single or a sequence of human actions. Being related to human behavior, the states identified for this group are *"standard", "delayed"* and *"no"*, applying the definitions provided in Section 2.1 dealing with the emergency response phases.
- ***Extensive needs*** (EN). Beside the characterization in terms of availability, some factors may also be represented by an extensive feature accounting for the quantity required to carry out the emergency response. Thus, the class of extensive need considers the quantity/amount of needs available on site, and it can be related to both technical needs and response activities. Elements contained within this group are represented by the states *"sufficient"* or *"not sufficient"*.

Table 2 shows how the 19 baseline factors are divided into the three above-defined groups. The table also reports the status that each factor may assume.

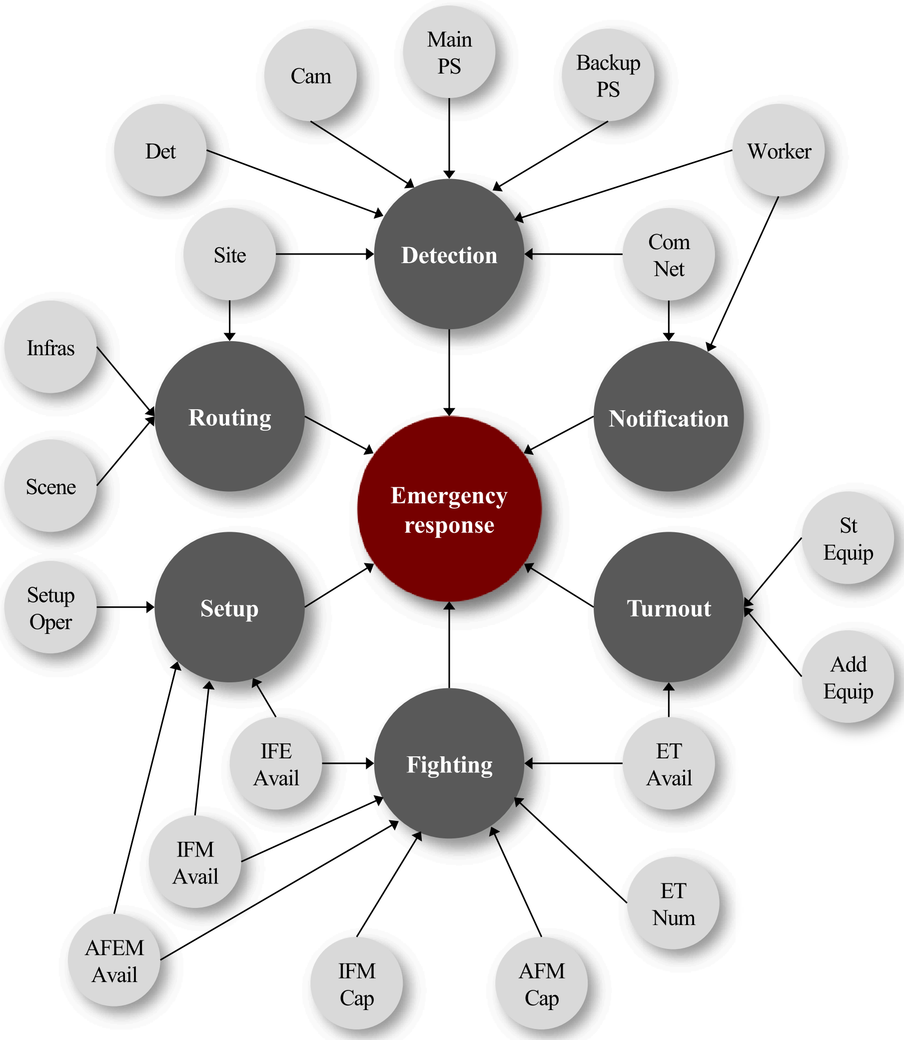

Fig. 2. The Directed Acyclic Graph of the Bayesian Network model developed in the present study. The emergency response node can assume two states: success and failure. Acronyms used to identify the nodes are reported in Table 2.

Table 3
Connections among factors and phases in the BN model developed in the present study. Acronyms are reported in Table 2. The symbol ∧ represents an "AND" connection, while ∨ is used for an "OR" connection.

Phases	Relation among factors
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 Num] ∧ [[IFE Avail ∧ IFM Avail ∧ IFM Cap] ∨ [AFEM Avail ∧ AFM Cap]]

2.3. *Step 2: characterization of baseline factors*

Given the lack of data available in the literature for the characterization of the factors and the limited information available concerning the effectiveness of the emergency response in cascading sequences triggered by natural events, the quantitative characterization of the identified baseline factors was based on expert elicitation. Expert elicitation is a widely recognized method to obtain informed opinions from individuals with particular expertise, and it is widely applied to assess the state of knowledge concerning a specific topic [45,63].

A specific survey was prepared and delivered to a total of 24 experts selected among Emergency Responders and Company Safety Managers sited in Europe, well above the minimum number of respondents identified by Cooke and Goossens [64] to obtain significant results from expert elicitation studies.

The survey consists of 4 sections divided as follows: *(i)* respondent's background, *(ii)* probability assessment of the state of each factor, *(iii)* probability assessment of the influence of each phase on the emergency response, and *(iv)* time assessment of the phases. The survey was administered to the group of experts through an anonymous online form. The experts involved in the survey carried out in the present study are safety managers of industrial sites and experienced firefighters with specific experience concerning chemical clusters and industrial plants. The selection of experts was made in line with the definition of expertise provided by O'Hagan et al. [65], who suggest that expertise does not necessarily require an in-depth knowledge of the subject matter but that experts may also be identified in persons who have the ability to organize and use that knowledge. The structure of questions of each section of the survey is reported in the Supplementary Material. Together with each question, the definition of the factor/phase under investigation was provided to respondents.

The first section of the survey was introduced to investigate the background of the respondents. In this section, statistics related to the affiliation and the years of experience were gathered. This information is typically considered a suitable trade-off between anonymity and objectivity [66].

The second section of the survey is related to the quantitative characterization of the baseline factors identified in Section 2.2. The objective of this part is to obtain the probability of each status for each factor. Experts were asked to answer the questions using the verbal scale reported in Fig. 1. A verbal scale was selected since it helps respondents to provide more intuitive answers [45,67]. The background translation into numerical values was carried out by the Likert-type scale proposed by Vagias [68] and reported in Fig. 1. The mean values calculated from the expert answers are considered in the following unless otherwise noted.

The quantification of each factor was carried out considering three triggers of the cascading sequence: internal causes (conventional accidents), earthquakes, and floods. It should be remarked that data for conventional accidents are reported in the literature for some of the factors [40,69,70]. In such cases, the question related to the conventional case was omitted.

The third section of the survey addresses the influence of the different phases of emergency response, as defined in Section 2.1, on the overall performance of the emergency response. To this aim, the influence of the *"delay"* status of each phase on the overall performance is assessed. Also in this case, the verbal scale reported in Fig. 1 is used and the mean values are calculated from the expert answers unless otherwise specified. The questions addressed the failure probability of the emergency response given a delay in the phase considered, $P_{failure}\,(\mathrm{PH} \mid delay)$.

The last section of the survey aims at quantifying 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. First, the time required in the case of conventional accidents was estimated, since this is an important benchmark to assess the possible delays caused by the consequences of the natural event in Natech scenarios. Then, the estimation of a credible delay range for each phase of emergency response caused by the natural events considered (earthquake and flood) was required to the experts.

Given the high experience of the responders, the questions were formulated using a numerical scale. A normal distribution was then used to assess the time required to perform each phase in cascading sequences triggered by conventional factors, calculating the mean μ and the standard deviation σ based on the answers received as reported in the Supplementary Material.

2.4. *Step 3: assessment of the emergency response performance*

A Bayesian Network (BN) approach was selected for the quantification of the emergency response performance (Step 3) since it provides a simple and complete tool for probability assessment, widely applied in the literature [71–77]. A brief overview of BN is reported in the Supplementary Material. This approach was also selected since Bayesian Networks do not limit the number of states potentially associated with a single node, allowing for a more detailed description of the factors considered. Nevertheless, it should be remarked that introducing several states for each factor leads to a higher number of input parameters needed for the quantification of the Conditional Probability Tables (CPTs).

Fig. 2 shows the Bayesian Network model developed in the present study. Root nodes are represented by the factors identified in Section 2.2, having mutually exclusive states. The factors in the BN model represent the parent node of the emergency response phases defined in Section 2.1, which in turn are the parent nodes of the single leaf node of the model that represents the emergency response.

A simplified approach was used for the quantification of the arcs, only accounting 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

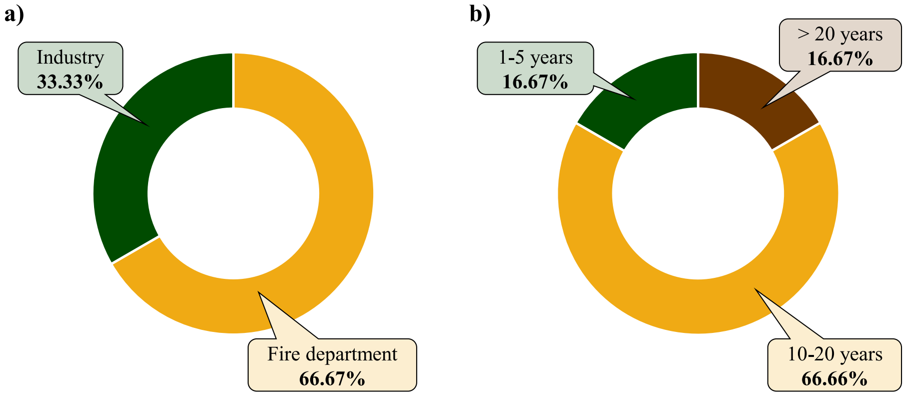

Fig. 3. Summary of (a) the background and (b) the years of experience of the experts that answered the survey.

nodes to get a positive outcome. The root nodes (i.e., the factors identified in Section 2.2) were then related to the phases according to the connections reported in Table 3.

Beside defining the type of connections among nodes, Conditional Probability Tables should be defined. The minimum set of CPTs necessary to characterize the entire BN model developed in the present study is reported in the Supplementary Material. The probabilities of the factors in the CPTs are those evaluated through the survey, as discussed in Section 2.3.

A binary evaluation was then introduced to simplify the assessment of the phase performance and of the overall emergency response performance. As introduced previously, the evaluation of the influence of a delay in a phase on the overall emergency response process is paramount. Thus, phases were converted into binary nodes, considering only their success or failure. The failure probability $P_{failure}$ of each phase is therefore defined as:

$$P_{failure}(PH) = P_{no}(PH) + P_{delay}(PH) \cdot P_{failure}(PH \mid delay) \tag{1}$$

where $P_{delay}(PH)$ and $P_{no}(PH)$ are the results of the quantified BN model and $P_{failure}$ $(PH \mid delay)$ is obtained from the survey (see Section 2.3). Clearly, the failure and the success probability of each phase add up to 1.

The emergency response (i.e., the leaf node of the model) is defined as a node characterized by two states: "*success*" and "*failure*". Successful emergency response requires that none of the phases fails. Thus, the CPT can be derived from that presented in the Supplementary Material.

The BN model is quantified for cascading sequences triggered by conventional factors, earthquakes, and floods. The quantification of the BN model in the case of conventional accidents represents a benchmark 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 in the case of natural events according to the following formula:

$$\text{Performance } (J, NE) = P_{\text{success}}\ (J, NE) / P_{\text{success}}\ (J, CA) \tag{2}$$

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

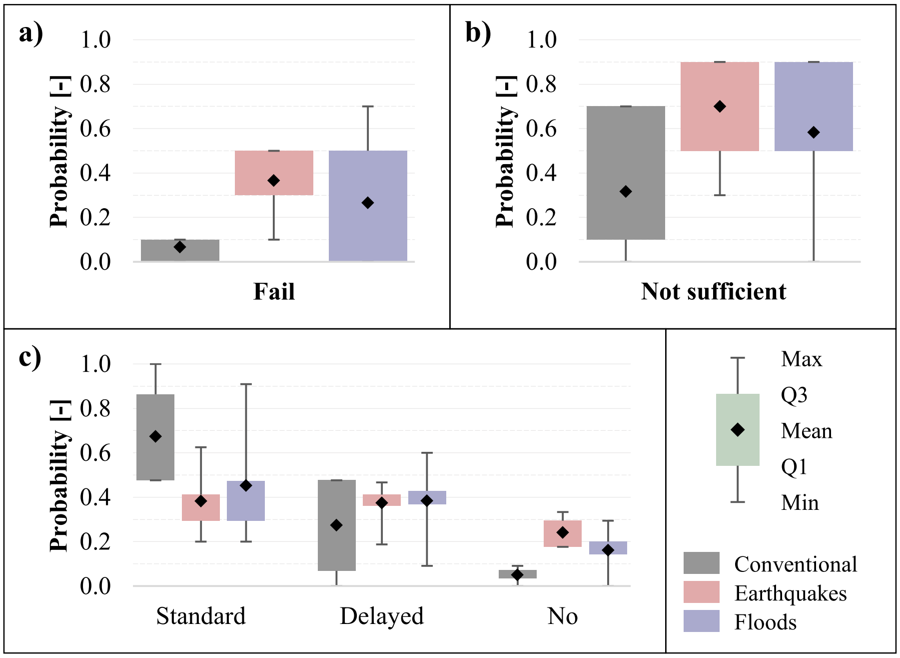

Fig. 4. Results of the survey for: (a) technical need "Standard equipment suitability"; (b) extensive need "Emergency teams number"; and (c) response activity "Emergency teams availability".

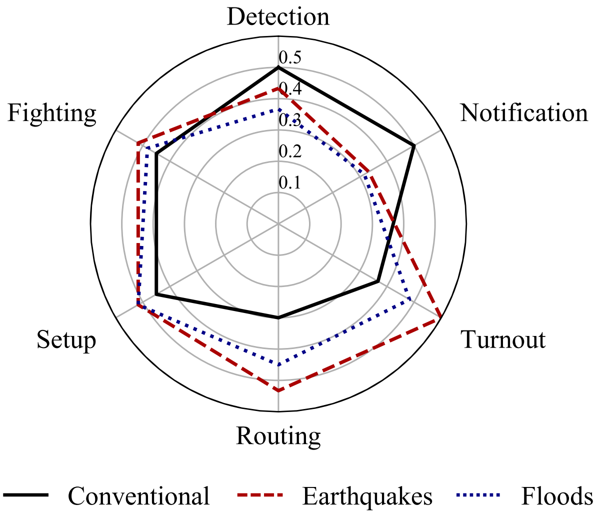

Fig. 5. Results from the survey concerning the probability of failure of the emergency response given a delay in each phase (see Section 2.3).

2.5. Step 4: assessment of the time required for emergency response

The last step of the methodology (Step 4) aims at assessing the time required for emergency response. Specifically, the time required 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 2.1, the phases considered in the time evaluation are detection, notification, turnout, routing, and setup. The firefighting phase is excluded from the present analysis for the following reasons:

- The duration of the firefighting phase depends on several factors. Among others, the specific features of fire that occur (such as the quantity and type of material involved in the fire) and the number of critical equipment items nearby the primary fire. In addition, firefighting time depends on the strategy adopted by emergency teams (e.g., fighting the fire or cooling the neighboring tanks), and on the number of emergency teams and the amount of firefighting material available, as discussed in Section 2.2. All these parameters are highly specific to the scenario of concern and to the characteristics of the industrial site affected. For this reason, a generic value of the duration of the firefighting phase would not represent a useful result in the framework of the present study.
- Several studies in the literature use an intervention time to assess the failure probability of a tank exposed to an external fire [28,29,46–52, 78], comparing it to the time to failure of the equipment item under analysis. In these studies, the intervention time is defined as the time lapse between the development of the primary fire and the start of mitigation or extinguishing actions. This definition is compliant with the choice of considering only the phases from the detection to the setup as the time for emergency response.

To assess the emergency response time, a Monte Carlo (MC) simulation was performed. This numerical method makes use of random sampling of the input variables in a given range to calculate the probability of the outputs of interest [79]. In the present study, MC simulation is used to assess the emergency response time in the case of cascading sequences caused by conventional accidents and natural events. The simulation considers as inputs both the results of the survey and of the Bayesian Network model. Concerning the survey, the data needed are the time distribution for conventional accidents and the extension of the delay in the case of natural events (see Section 2.3). As for the BN, the results concerning the phases are used to define whether to apply or not a delay factor in the case of cascading sequences triggered by natural events (see Section 2.4). As outputs, the probability distribution of time required to conclude each phase as well as the overall emergency response is obtained in the case of conventional and Natech accidents. The complete procedure applied for the evaluation is reported in the Supplementary Material. Four simulations were performed testing different orders of magnitude in the number of repetitions, specifically $1{\cdot}10^4$, $1{\cdot}10^5$, $1{\cdot}10^6$, and $1{\cdot}10^7$. A low accuracy was obtained when considering $1{\cdot}10^4$ repetitions, while the results were comparable in the other cases. Thus, the selected number of repetitions was $1{\cdot}10^6$, considering a trade-off between accuracy and computational cost [79–81]. The detail of the results obtained from MC simulations is reported in the Supplementary Material.

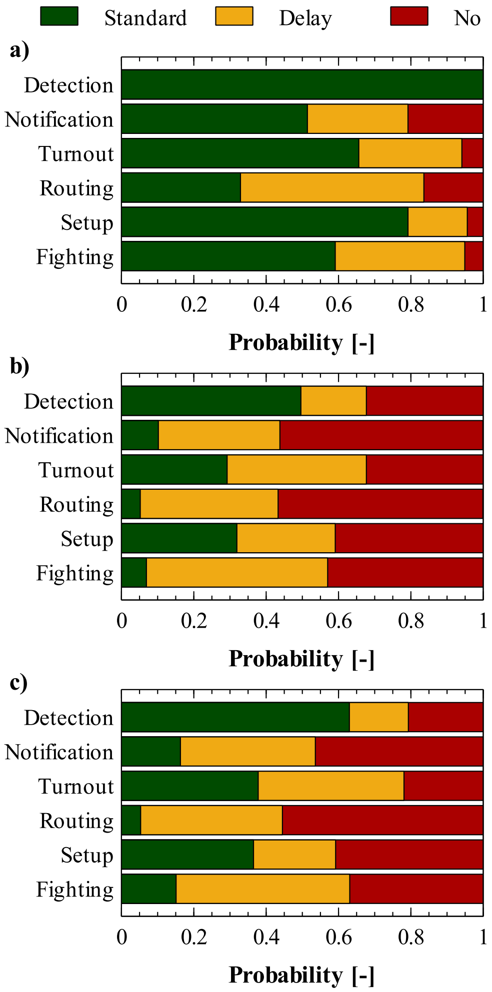

Fig. 6. Probabilities of the status of each phase of emergency response considering cascading sequences triggered by (a) conventional accidents; (b) earthquakes; and (c) floods according to the quantified BN model.

3. Results

3.1. Results of the expert elicitation

A total of 6 answers were collected from the survey, which represents a significant set of data based on the study by Cooke and Goossens [64]. Fig. 3 shows the information on the background of the experts. As shown in the Figure, the majority of the experts work in fire departments (4 out of 6 respondents) and the remaining part in industrial sites. Furthermore, all respondents have considerable experience in their field, and most of them have more than ten years of experience (5 out of 6 respondents).

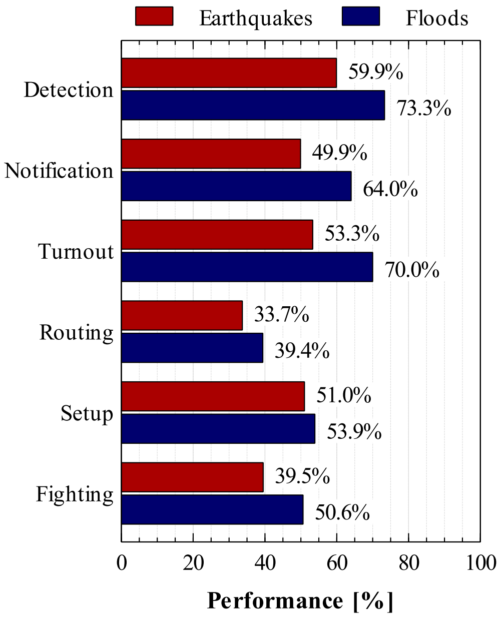

Fig. 7. Performance of each phase of emergency response (expressed as % of the baseline performance expected in conventional accidents) in the case of cascading sequences triggered by earthquakes (red bars) and floods (blue bars).

Fig. 4 shows an example of the results from the expert survey, concerning the characterization of the factors included in the present study. In particular, the figure reports the results of the expert survey with respect to the “*standard equipment suitability*” (a technical need, Fig. 4a), the “*emergency teams number*” (an extensive need, Fig. 4b), and the “*emergency teams availability*” (a response activity, Fig. 4c). The results obtained for all the 19 basic factors are reported in the Supplementary Material. As clearly shown in Fig. 4, the probability of failure or of delay of all the three factors considered is always higher in the case of cascading events triggered by earthquakes or floods (red and blue plots) than in the case of conventional failures (gray bars). Similar results are obtained for all the factors considered irrespectively of the category to which they belong, as shown in Table C1 of the Supplementary Material.

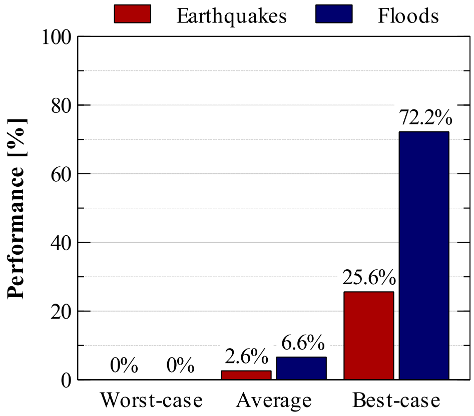

Fig. 9. Overall performance of emergency response (expressed as % of the baseline performance in conventional accidents) in the case of cascading events triggered by earthquakes (red bars) and floods (blue bars).

Fig. 5 shows the failure probability of the emergency response assuming a credible delay in each phase, $P_{failure}$ (PH | *delay*), estimated from the expert survey in the case of earthquake and flood (see Section 2.3). According to the results shown in the figure, the possible delay of each phase in the case of earthquakes is considered more critical than in the case of flood events, leading to a higher failure probability in all the phases of the emergency response. Moreover, two different trends can be identified in the figure. In the initial two phases of emergency response, Detection and Notification, the failure probabilities given a delay are higher when the cascading sequence is caused by a conventional accident than a natural event. This should not be surprising considering the specificities of these two phases. Indeed, the natural event itself represents the first alarm for emergency managers and emergency teams. Therefore, it is credible that immediately after the occurrence of the natural event the emergency teams and emergency managers are alerted and inspection of the site is started as soon as possible. Differently, in the final phases of emergency response, from Turnout to Fighting, the delays in the case of cascading sequences triggered by natural events are considered more critical, due to the possible disruptions caused by the natural event. The corresponding failure probability is thus higher than considering conventional accidents. Specifically, the Turnout and Routing phases are those more likely to be affected by a possible delay.

3.2. *Performance of emergency response*

The results of the expert survey discussed in the previous section represent the input parameter for the quantification of the BN model

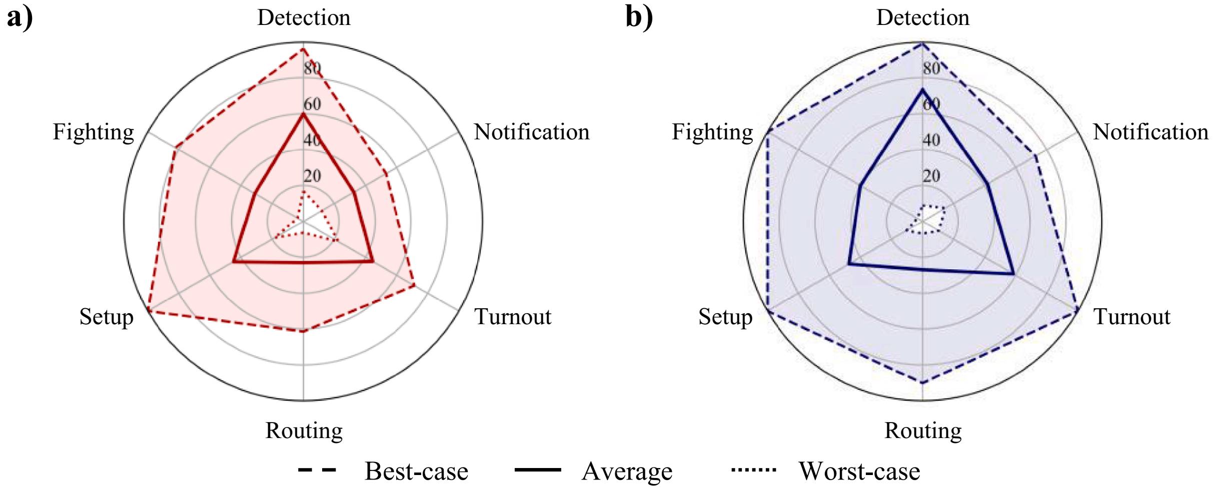

Fig. 8. Performance of each phase of emergency management (expressed as % of the baseline performance in conventional accidents) considering average, best-case, and worst-case answers from the survey as an input to the BN quantification procedure. (a) Cascading events triggered by earthquakes; (b) Cascading events triggered by floods.

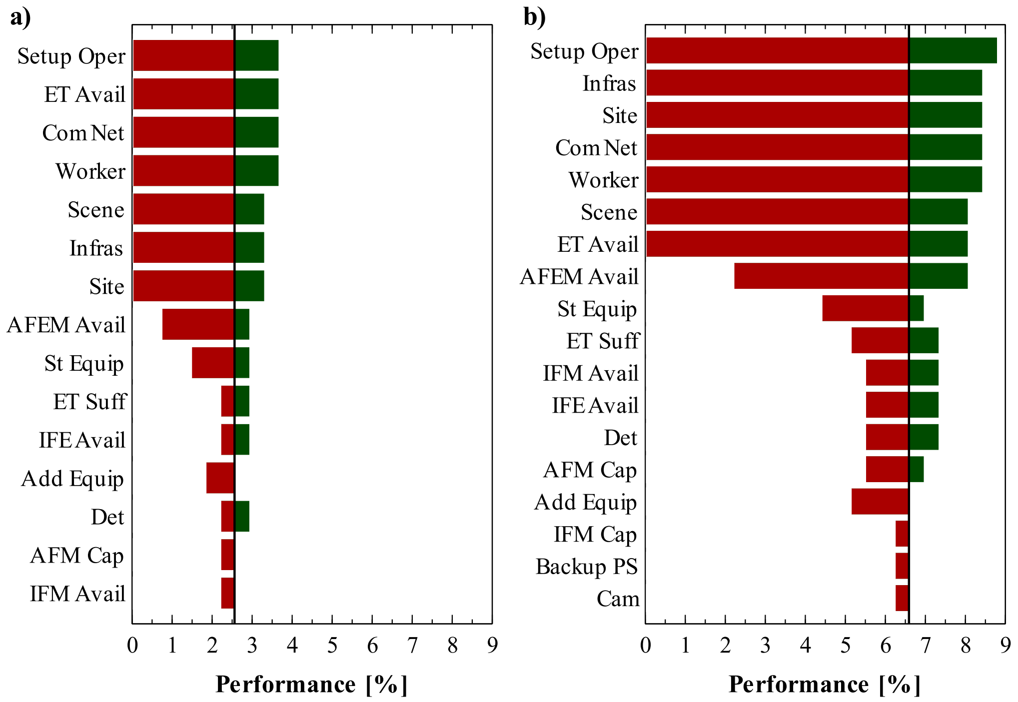

Fig. 10. Tornado charts reporting the results of the sensitivity analysis of emergency response performance for cascading events triggered by (a) earthquakes and (b) floods. Overall performance is expressed as % of the baseline performance in conventional accidents. Acronyms are reported in Table 2.

developed in the present study (see Fig. 2). The procedure for the quantification of the BN is described in Section 2.4.

Fig. 6 shows the probabilities of the status of each phase of emergency response respectively considering cascading sequences triggered by conventional accidents (panel a), earthquakes (panel b), and floods (panel c) according to the quantified BN model. Regardless of the phase of emergency response, the quantification of the BN model reports that the probability of the *"standard"* status is much lower when considering cascading sequences triggered by earthquakes and floods concerning those induced by conventional causes. This result confirms the strong impact attributed by experts to a natural event on all phases of the emergency response.

The degradation of the performance of emergency response in the case of cascading sequences triggered by natural events was benchmarked to that of emergency response in cascading sequences triggered by conventional accidents. Specifically, a quantitative response factor was calculated dividing the emergency response performance in the case of natural events with respect to the baseline data obtained for emergency response in the case of conventional scenarios (see Eqs. (1) and (2) in Section 2.4). The results are reported in Fig. 7 for both the natural events considered in the study: earthquakes (red bars) and floods (blue bars). As shown in the figure, all phases of emergency response are strongly affected by the occurrence of natural events: the higher value of the performance factor is about 75 % for the detection phase in cascading sequences caused by floods. Fig. 7 also shows that the Routing phase is the most likely affected when considering emergency response after or during natural events, followed by the Fighting phase and the Setup phase, with values of the performance factor always lower than 55 %. Thus, in emergency planning, priority efforts should be dedicated to improve the performance of such phases in the case of emergency response after earthquakes or floods.

In order to analyze the agreement between experts and the uncertainty in the results, the BN model was used also to quantify the performance considering the best-case and worst-case answers to the survey. In Fig. 8 the performance obtained considering the best-case and worst-case answers as inputs to the BN model are reported for cascading sequences triggered by both earthquakes (panel a) and floods (panel b). As shown in the figure, the performance of each phase changes considerably when considering the best and worst-case answers, confirming the presence of a relevant uncertainty concerning the actual performance of emergency response in Natech scenarios. However, it is important to remark that the average values are always closer to the worst-case figures than to the best-case results. Thus, even taking into account the uncertainty, the results confirm the need to improve the performance of the emergency response in the case of cascading sequences triggered by natural events.

Fig. 9 reports the value of the overall performance factor of emergency response in cascading events triggered by earthquakes and floods calculated from the BN model. The Figure also includes the results obtained considering the best-case and worst-case answers obtained from expert elicitation. As evident from Fig. 9, the average values of the overall performance factor of the emergency response are very low, respectively 2.6 % in the case of earthquakes and 6.6 % in the case of floods. This confirms that the emergency response is strongly influenced by the occurrence of natural events and that the probability of success is far lower than that experienced in conventional accidents. More specifically, the Figure also shows that earthquakes are considered likely to affect the emergency response more than floods, leading to a lower value of the probability of success of emergency response. Finally, the results confirm that a relevant uncertainty is present among experts. It is worth to remark that the discrepancies in the expert opinions may depend, at least in part, on the different exposure to natural hazards of the geographical areas where the experts are based. Clearly enough, this may result in a different preparedness and a different magnitude of the natural events experienced by the responders, thus influencing their answers.

3.3. Sensitivity analysis of the Bayesian network model

The results obtained from the survey and the quantified BN model confirm that emergency response is expected to be strongly influenced by the occurrence of natural events such as earthquakes and floods. The analysis of the performance of each phase of emergency response has also identified those more likely to be impacted by the natural events

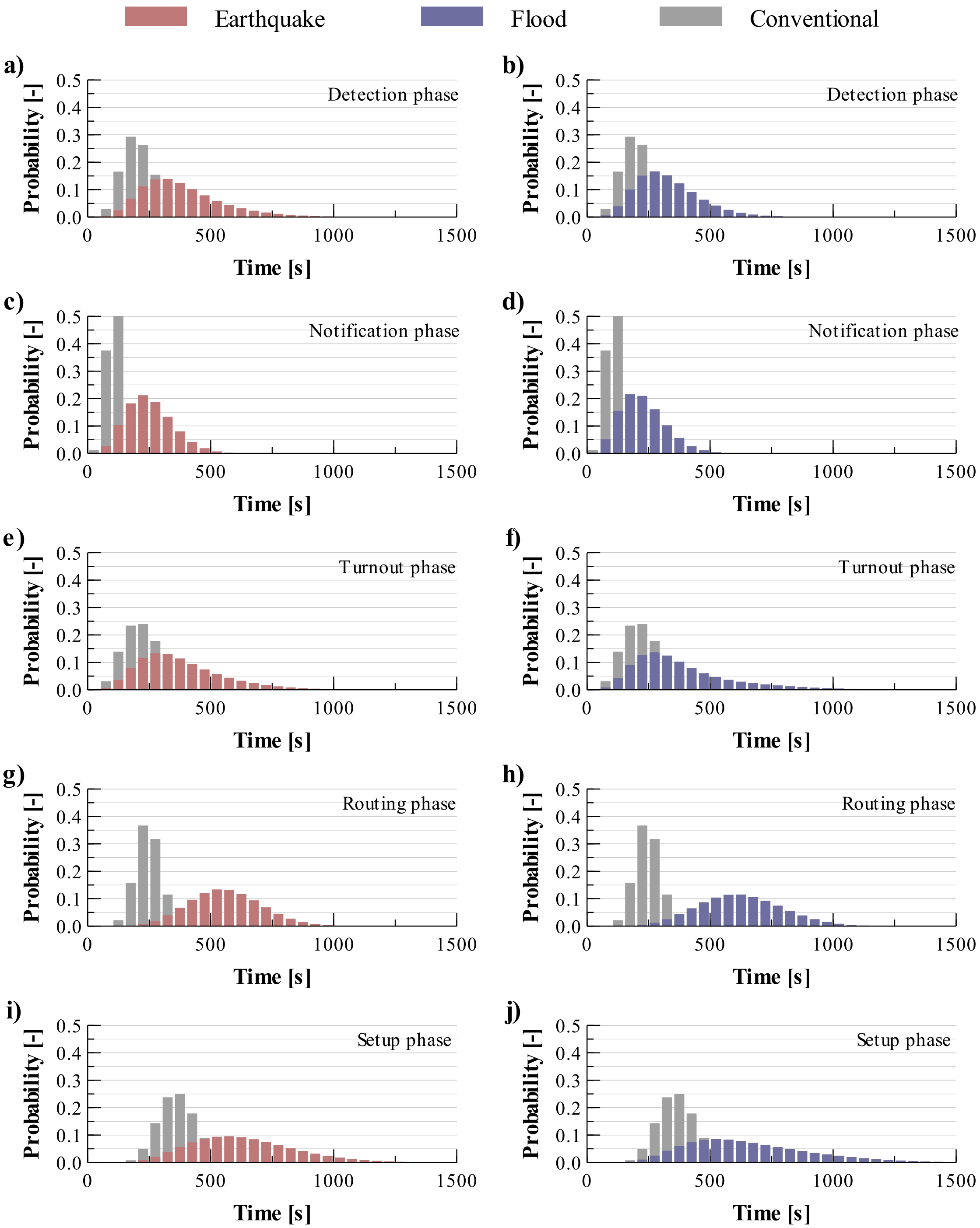

Fig. 11. Probability distribution of the time required to complete each phase of the emergency response in the case of cascading events having conventional causes (gray curve) and cascading sequences triggered by earthquakes (left side, red curves, panels a, c, e, g and i) and floods (right side, blue curves, panels b, d, f, h, and j). Detection phase: panels a and b. Notification phase: panels c and d. Turnout phase: panels e and f. Routing phase: panels g and h. Setup phase: panels i and j.

considered. In this framework, the identification of the critical factors whose failure or depleted performance may affect each phase of the emergency response is paramount for the development of effective emergency plans aimed at increasing the emergency response performance in cascading sequences triggered by natural events. 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, considering two extreme situations:

- The lower bound, representing the worst possible scenario, accounts for the total unavailability of the factor.
- The upper bound, representing the best credible scenario, considers the value estimated in the case of conventional accidents, thus providing the best expected performance.

By this approach, the factors mostly affecting the emergency response in the case of cascading sequences triggered by natural events are identified. The results of the sensitivity analysis on the overall emergency response are reported in Fig. 10 for cascading sequences triggered by earthquakes (panel a) and floods (panel b). The same analysis was carried out considering each phase of the emergency response, and the specific results are reported in the Supplementary

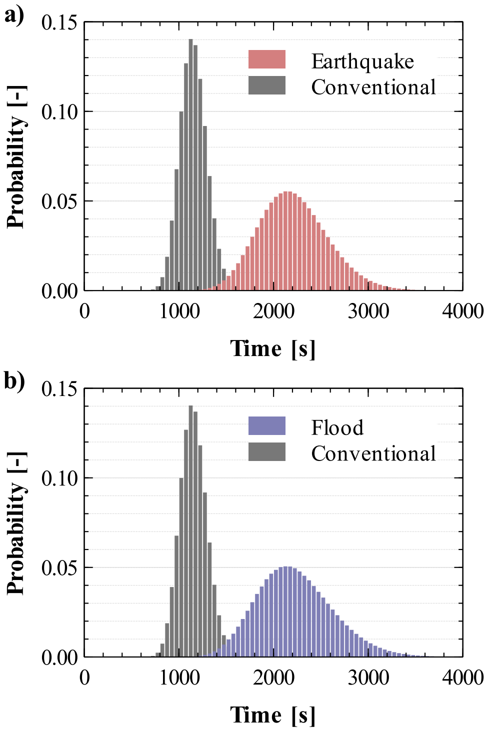

Fig. 12. Probability distribution of the time required to complete the emergency response in the case of cascading events having conventional causes (gray curve) and cascading sequences triggered by (a) earthquakes and (b) floods.

Material. As can be observed in Fig. 10, the ability to carry out the setup operations is the most critical for both earthquakes and floods. Thus, any improvement that allows increasing the probability of success of this task leads to a relevant increase in the emergency response performance. Concerning the other factors showing a high criticality in the case of earthquakes, these are the availability of emergency teams, the communication network, and worker availability. In addition, the three factors related to the routing phase (i.e., the accessibility of external infrastructure, site, and scene) are also particularly relevant. In the case of floods, the accessibility of the external infrastructure and of the site, the communication network, and the worker availability are found to be the more critical factors.

3.4. *Time required for emergency intervention*

The time required for emergency intervention is calculated by the methodology described in Section 2.5. First, the evaluation is performed by considering each phase separately and characterizing it using the data collected from the expert survey for the case of cascading sequences caused by conventional accidents. The results of the quantified BN model are then used to calculate the time required for emergency response in the case of earthquakes and floods. It is worth remembering that due to its specificity, the Fighting phase is excluded from the analysis, as explained in Section 2.5.

Fig. 11 shows the probability distribution of the time required to complete each phase of the emergency response respectively in the case of cascading events triggered by conventional accidents (gray bars), by earthquakes (red bars), and by floods (blue bars). Clearly enough, the time required to complete all the phases is higher when considering cascading sequences triggered by natural events than in the case of sequences triggered by conventional accidents. Nevertheless, the phases of emergency response are differently affected by natural events. Indeed, the increase in required time is lower in the initial phases of emergency response (from Detection to Turnout). This may be explained considering two main factors. On the one hand, these are the phases whose performance is less affected by the occurrence of natural events, as shown in Figs. 7 and 8. On the other hand, the duration of these phases is lower than the others. The average times for the detection, notification, and turnout phase range from 90 s to 120 s in conventional scenarios according to the information retrieved from the expert survey, while the average values reach up to over 300 s for the last two phases (see Table C3 in the Supplementary Material). All these factors contribute to the significantly higher increase in the time required to complete the routing and setup phases compared to the detection, notification, and turnout phases.

Based on the characterization of the time required to carry out each phase of emergency response, the total time needed for the response is also assessed. Fig. 12 reports the probability distribution of the time required to carry out the overall emergency response in the case of cascading sequences triggered by earthquakes and floods. The Figure also reports a comparison with the time required in cascading events triggered by conventional accidents. A similar trend is obtained for the probability distribution of the time required for emergency response estimated for accidents triggered by earthquakes and floods. However, a significant increase is observed in the time required to carry out the emergency response in the case of cascading sequences triggered by natural events with respect to that required in conventional scenarios.

The time required for the emergency response ranges from about 13 to 25 min in conventional scenarios (see Fig. 12). The upper bound value is in line with that proposed by Landucci et al. [28], while a more conservative value is obtained in the present study for the lower extreme. In the case of earthquakes and floods, the time required for emergency response is higher, ranging between 20 and 60 min. Such differences result as well in a relevant difference in the most probable time value for the emergency response among Natech and conventional scenarios. Indeed, a value of about 19 min is estimated in the case of conventional cascading scenarios, while in the case of Natech scenarios a value of about 35 min. It should be remarked that, in the case of Natech accidents, the median time value results in about 40 min, thus higher than the most probable time value, differently from conventional scenarios where almost coincident values are obtained. Overall, a delay factor of about 1.8 is obtained in the case of earthquakes and floods when considering the most probable time value required for emergency response.

As discussed in Section 2.5, the time values reported in Fig. 12 do not include the Fighting phase. The results obtained from the survey indicate that the Fighting phase can last up to 3 times the duration experienced in conventional cascading events when considering earthquakes. The duration is expected to be even longer in the case of floods, where the time required to complete the Fighting phase is estimated to be up to 4 times higher than conventional cascading events.

3.5. *Mitigation of cascading scenarios*

The results obtained are of particular importance when considering emergency response aimed at preventing the escalation triggered by fires in the framework of the mitigation of cascading scenarios. Several previous studies evidenced the relevance of emergency response in preventing the failure of atmospheric and pressurized equipment items leading to escalation [28,29,82,83]. In particular, both the probability of failure on demand of emergency response [29,84] and the time for the displacement of mitigation actions [50,85,86] were highlighted as crucial to prevent domino effects leading to escalation and cascading scenarios. In this framework, the results obtained in the present study provide new insights concerning the probability of escalation in Natech scenarios with respect to conventional accidents when considering the performance of a non-technical safety barrier as the emergency response.

Actually, in the methodology originally proposed by Landucci et al. [28], the probability of domino effects leading to escalation is estimated

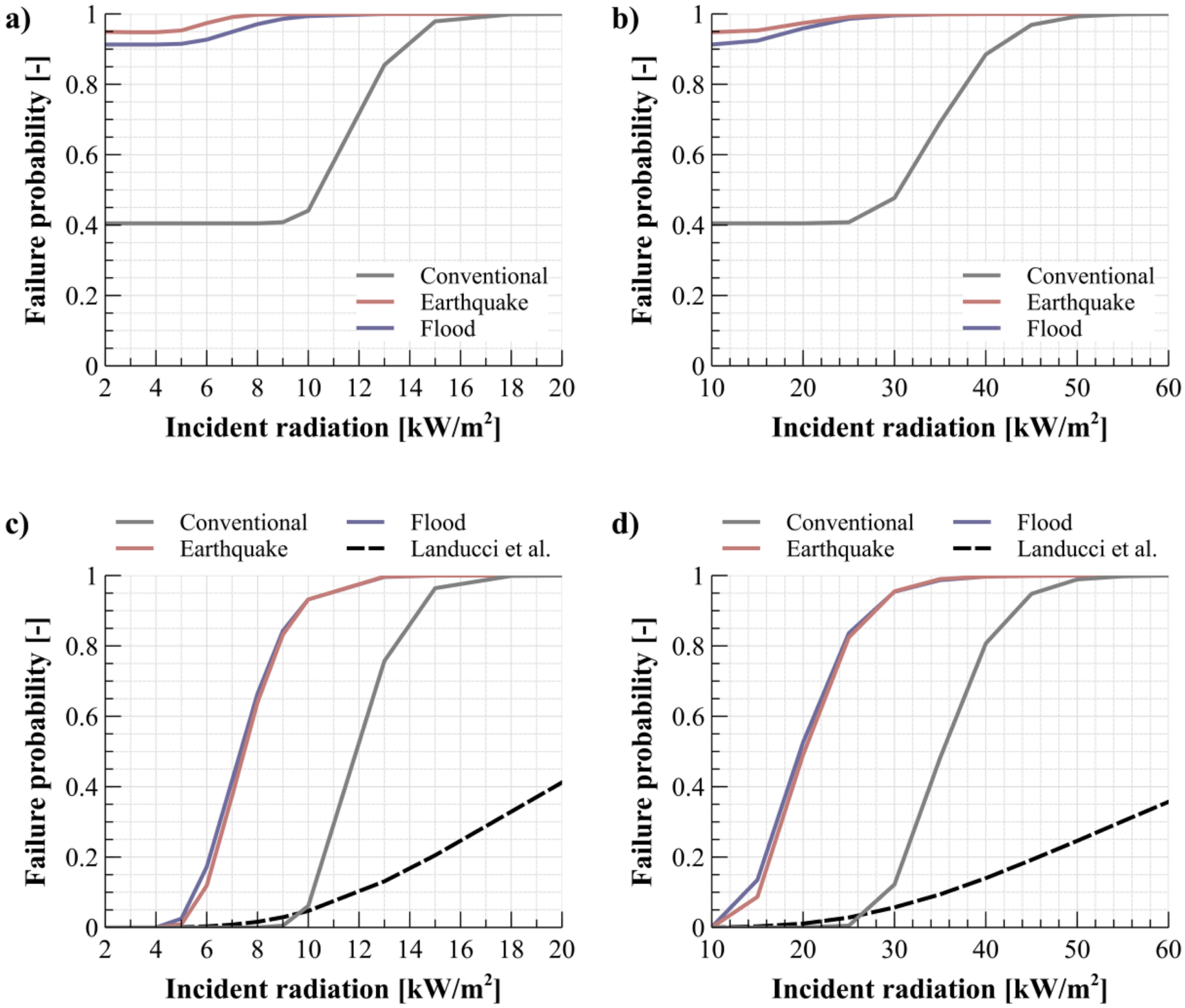

Fig. 13. (a) Overall failure probabilities as a function of the radiation intensity for a 100 m^3 atmospheric tank and (b) for a 200 m^3 volume pressurized vessel. (c) Failure probabilities as a function of the radiation intensity calculated considering always successful emergency response has a function of the radiation intensity for a 100 m^3 atmospheric tank and (d) for a 200 m^3 volume pressurized vessel. The failure probabilities in the presence of emergency response calculated applying the correlation by Landucci et al. [28] are also reported in panels (c) and (d).

comparing the Time To Failure (TTF) of vessels exposed to fires to the Time To Mitigation (TTM), which is the time required to display the emergency response. The TTF of storage and process vessels may be assessed applying simplified correlations widely used in the literature [36]. Less attention was devoted to date to the assessment of TTM, which is strongly affected by the performance of emergency response, in particular when Natech scenarios are of concern [61,62]. The results obtained in the present study provide a specific assessment of the probability of failure on demand of the emergency response and of the probability distribution of the TTM based on an in-depth analysis of emergency response, which may be used for an improved assessment of the probability of escalation triggered by fire.

In order to demonstrate the potentiality of the methodology, specific simulations were carried out to calculate the failure probability of tanks exposed to external fires. A representative dataset of atmospheric and pressurized tanks and radiation intensities was considered. The features of the tanks included in the analysis are reported in Table I1 in the Supplementary Material, together with the radiation values considered and the calculated TTF values. Emergency response was assumed as the only available mitigation action aimed at preventing escalation. Monte-Carlo simulations were used to assess the probabilities of failure considering the TTM distribution and the probability of failure on demand of the emergency response obtained in the present study and reported respectively in Figs. 6 and 12. The details of the procedure and of the calculations are reported in the Supplementary Material.

Fig. 13 reports an example of the results obtained for an atmospheric storage tank and for a pressurized storage tank. Very similar results were obtained for all the tanks considered, and are reported in Table I2 and Table I3 in the Supplementary Material. As shown in Fig. 13, in complex cascading scenarios the overall probability of failure of atmospheric and pressurized vessels due to fire is high, as a consequence both of the high probability of failure on demand of emergency response and of the increase in the time of the response. Actually, even in the case of cascading events triggered by conventional scenarios, the probability of failure of vessels exposed to fire is high, in particular when radiation intensities higher than 60 kW/m^2 are considered, corresponding to flame engulfment and/or impingement. It should be considered, though, that other technical and non-technical active and passive mitigation barriers, that may be present to prevent escalation, are not considered in the analysis (e.g., water deluges, fireproofing, etc.).

When cascading events in Natech scenarios generated by earthquakes or floods are considered, even higher probabilities of failure are obtained. As evidenced in Fig. 13, the possible degradation of emergency response results in a dramatic increase of the escalation probability. This result is in agreement with evidence from past accidents and with the previous results obtained by Misuri et al. [45,61,62], highlighting that emergency response was not possible and both technical and non-technical safety barriers are expected to be unavailable and/or

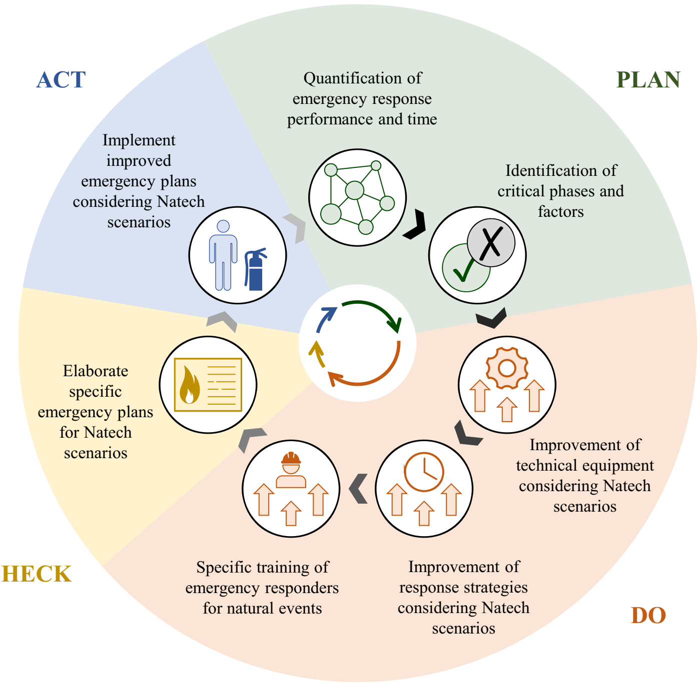

Fig. 14. Example of PDCA (Plan-Do-Check-Act) cycle aimed at improving performance in emergency response in cascading events caused by natural events.

to have a higher probability of failure on demand in severe Natech scenarios.

Fig. 13 also reports a comparison of the time to failure of the two sample vessels calculated considering always successful the emergency response, but accounting for the delay in its displacement. in the case of conventional and Natech scenarios calculated in the present study with that estimated by Landucci et al. [28]. Comparing the values, it is evident that the higher delays in emergency response obtained from the model developed in the present study cause higher failure probabilities of tanks, both considering conventional and Natech accidents as triggers of the cascading sequence. Thus, the results reported in Fig. 13 suggest that an underestimation of the escalation probability is obtained when applying the correlation developed by Landucci et al. [28]. It should be highlighted that the results obtained in the present study are based on a detailed analysis of all the steps of emergency response, not considered in the study of Landucci et al. [28].

4. Discussion

The present study provides for the first time figures addressing the expected probability of failure on demand of emergency response in cascading accidents triggered by earthquakes and by floods. A specific Bayesian Network model was developed to assess the emergency response performance and Monte Carlo simulations were performed to evaluate the emergency response time. Due to the lack of quantitative data from past accidents on emergency response, the quantification of the models was based on expert elicitation, which represents an effective route to collect quantitative information.

Thus, on the one hand, the results obtained in the present study represent an advancement in the assessment of the emergency response in cascading accident scenarios triggered by natural events. On the other hand, caution should be paid in the direct application of the results, since those provided are baseline data, not considering site-specific factors and the possible bias of expert judgment. Nevertheless, the expert elicitation carried out in the present study, based on a general framework, allows obtaining a general assessment of the emergency response and baseline quantitative data concerning the success probability and the required time of the response. The BN model and the MC simulation may be applied as well to include site-specific data, provided that a specific survey is carried out and/or specific experience on emergency response is available for the site of concern to update the BN and the probability values.

The model developed also represents a valuable tool to improve the emergency management of Natech scenarios. This is of particular importance when considering emergency planning. Fig. 14 shows a Plan-Do-Check-Act (PDCA) cycle aimed at enhancing the specific performance of emergency response in Natech scenarios. Starting from the assessment of the current status of the emergency response (obtained by the approach developed in the present study supported either by the baseline data reported above or by a site-specific expert elicitation), the developed methodology allows for the quantification of the emergency response performance and required time. A sensitivity analysis, as shown in Section 3, can be used to identify the phases and factors of the emergency response mostly affected by natural events. Based on the results of the sensitivity analysis, improvements in the technical features, the strategies, and the training of responders may be introduced: e.g. the availability of amphibious vehicles and the identification of routes to reach the industrial site can improve the performance of the emergency response in the case of flood events; the specific training of emergency responders to the specific features of Natech events may improve their performance. Specific emergency plans for Natech scenarios may then be elaborated and implemented. Once the changes are implemented, the overall performance of the emergency response can be reassessed, providing new figures related to the probability of success and the time of emergency response. In principle, this virtuous cycle can continue until e.g. a target value for the time for emergency response is obtained.

The methodology developed in the present study may also be useful in the framework of the quantitative risk assessment of cascading sequences triggered by Natech accidents. Indeed, the methodology can be applied to derive specific escalation probabilities due to the failure of equipment items involved in fire, taking into account the probability of failure on demand and the time required to carry out emergency response. This aspect becomes even more relevant considering that recent studies evidenced the importance of procedural safety barriers as emergency response in determining the actual risk figures, considering both conventional cascading scenarios [29] and Natech scenarios [61, 62]. Thus, the methodology developed provides a sound approach to the quantification of specific figures for the probability of success of mitigation actions and intervention time carried out during emergency response which may support a more reliable quantitative risk assessment of cascading scenarios triggered by Natech accidents.

5. Conclusions

Natech accidents have become of particular concern in the last decades due to the increasing number of intense natural events reported worldwide and to the severe consequences that may arise from such accidents. A relevant feature of Natech accidents is the probable development of cascading scenarios, and, among others, of fire scenarios. Emergency response is the most effective safety barrier in the mitigation of fire scenarios and in the prevention of escalation leading to domino scenarios. However, natural events may affect the emergency response, reducing the effectiveness of the intervention and increasing the time required to deploy the mitigation actions. The Bayesian Network model developed allows for quantifying the specific performance of the emergency response in both conventional and Natech cascading scenarios. The use of Monte Carlo simulations provided baseline values for the probability distribution of the time required for emergency response in the presence of specific natural events based on expert judgment. The results show that the probability of failure on demand of emergency response is about two orders of magnitude higher than that expected for cascading events having conventional causes. The routing and setup phases are the phases most likely affected by natural events. The time required to perform the emergency response in the case of earthquakes and floods may be more than doubled with respect to conventional accidents. The methodology developed in the present study may support the improvement of emergency response plans and procedures, allowing the development and assessment of specific emergency plans for Natech scenarios. Moreover, the developed approach can be used to obtain specific figures for the probability of fire-driven escalation in Natech scenarios, thus contributing to a more accurate assessment and management of the risk due to Natech scenarios.

CRediT authorship contribution statement

Federica Ricci: Writing – original draft, Methodology, Investigation, Conceptualization. **Ming Yang:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Genserik Reniers:** Writing – review & editing, Supervision, Conceptualization. **Valerio Cozzani:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ress.2023.109820.

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