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A short-cut tool to manage NaTech risk in chemical industry due to floods

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Industrial sites are frequently built close to large rivers and coasts in order to facilitate the supply of raw materials, the export of products and the exchange of goods. However, these arrangements expose the equipment to the risk of being involved in floods or coastal surges. The hazard can be considerably increased when the establishment is a Seveso industry, i.e. an establishment classified as at major accident hazard according to the Directive 2012/18/EU, also known as the Seveso III Directive. Accidental scenarios due to the release of hazardous materials, triggered by natural phenomena, are named NaTech (Natural Technological event). In Europe, during the last decades, the frequency and severity of extreme natural phenomena giving rise to NaTech events in Seveso industries is growing. Hundreds of Italian Seveso establishments are exposed to flood risk, for this reason this work aims improving a short-cut tool for the dynamic assessment of NaTech risk triggered by flood waves and floods. This tool supports emergency managers in choosing the best strategies to implement actions mitigating the consequence of this type of event. It consists of a Bayesian network in which the frequency and magnitude combined with information about the vulnerable elements (included in the territory), deefined as discrete variables, make possible to quantify a NaTech risk index. This index is updated in real time according to the local conditions. The approach has been applied to an Italian case study.

Keywords: NaTech event, risk management, dynamic risk assessment, flood, Bayesian network.

1. Introduction

Technological incidents, originated by the impact of a natural event on an industrial facility, is named NaTech event, which is the acronym of Natural-Technological event (Clerc and Le Claire, 1994; Cruz et al., 2004). NaTech events are more severe when hazardous substances are stored or processed in the establishment hit by the natural phenomenon; the consequent scenarios can be catastrophic for workers, the external population and the environment (Lindell and Perry, 1996; Steinberg et al., 2008; Cruz and Okada, 2008). Floods are amongst the most common extreme natural events affecting many industrial activities (World Meteorological Organization, 2008). The reason is because human activities are mainly concentrated along the coasts and close to large rivers in order to facilitate both the supply of raw materials and the transport of products. In recent years, there has been a numerical increase in floods waves that affected anthropized territories; this evidence is due to several causes: (i) the urban expansion, which led to the cementation, shrinkage and/or deviation of natural fluvial paths, (ii) the hazard characteristics of the territory and the orography around the anthropogenic activities, and (iii) the climate change.

Several NaTech events are reported by the literature. In the mid-1990s, an oil depot was destroyed by a flood in Egypt. In 2002 some fires and explosions occurred in a refinery in Marocco due to the release of hazardous substances triggered by a flood. In the USA, toxic contamination and long-term risks for residents were some consequences of the Hurricane Katrina occurred in 2005. In 2011, a serious oil spill into the Tyrrhenian Sea was caused by a flood that hit a refinery in South Italy; whereas, in 2017, a similar event occurred in another Italian refinery located in the Central-North of the country. An Italian working group started focusing on the study of NaTech events (Italian Natech Working Group, 2016); the group observed that in the European context, there were over 200 major events which caused fires, explosions, and dispersions of toxic substances in the period between 1980 and 2000.

From the legislation point of view, the Directive 2012/18/EU, commonly known as the Seveso III Directive, represents the normative relating to the control of industrial accidents involving the use or storage of dangerous substances which can cause major accident; in Italy, it has been transposed into the Decree Law n. 105/2015 (Decreto Legislativo, 2015). The Directive the EU 2022/2557, whose short name is CER (Critical Entities Resilience) Directive, aims reducing the vulnerabilities and strengthening the physical resilience of critical infrastructure, such as industrial plants, also from threats from natural phenomena. Since the focus of this work is on NaTech originated from floods, it is also necessary to introduce the legislation that deals with these natural phenomena; this is the Flood Directive (2007), implemented in Italy by the Decree Law n. 49/2010 (Decreto Legislativo, 2010).

Given the complexity of NaTech events, the traditional risk management tools are not sufficiently able to deal with this type of scenarios. Some scholars developed specific tools and methods to analyse these accidents. As an example, Marzo et al. (2015) defined a short-cut approach assessing the vulnerability of a territory to seismic Na-Techs; Cozzani and coauthors (2014) developed an approach to evaluate the domino effects due to NaTech triggered by earthquakes; Steinberg and Cruz (2004) described the lessons learned from the analysis of the strong earthquake that involved Turkey in 1999; Milazzo et al. (2013) and Ancione et al. (2014) estimated the vulnerability respectively of industrial facilities and wastewater treatment facilities to volcanic NaTech; Kadri et al. (2014) analysed the impact of natural disasters on critical infrastructure; Luo et al. (2022) provided a web-based Geographic Information System (GIS) tool to collect, analyse and share historical data of NaTech events supporting risk managers in understanding the geographical distribution of historical events.

Other researchers developed approaches to evaluate NaTech risks using some Bayesian Networks (BN), amongst these the following can be mentioned: Khakzad e van Gelder (2018) proposed a method for assessing the fragility of industrial structures exposed to flooding; Naderpoura and Khakzad (2018) used a BN in order to approach the study of NaTech scenarios as a domino effect; Petrlova and Polorecka (2018) converted a Fault Tree Analysis and an Event Tree Analysis into a BN focusing on scenarios where the loss of containment is caused by the impact of a natural phenomenon. Ancione and Milazzo (2021) provided a dynamic tool for the risk manager, which supported in giving a quick awareness about the changes of the probability distribution of a NaTech risk index during the occurrence of an extreme natural event.

In this work, a short cut tool that supports risk managers during emergency phase due to a NaTech event triggered by flood is shown. The manuscript is organised as follows: Section 2 defines the approach, Section 3 introduces the case-study, Section 4 provides results and discussion, and finally in the Section 5 gives some conclusions.

2. Methodology

The approach proposed in this work is named Dynamic Risk Analysis for NaTech (DRAN). It consists first of the assessment of NaTech risks for each industrial plant and the updating of elements that characterise the NaTech event.

To perform the risk analysis, the Event Tree technique has been applied to quantify the probability of each scenario and to calculate the probability of intermediate events. The potential of release (release, Pn) of the hazardous materials, in turn, depends on the vulnerability (V), i.e. the probability that an equipment can be damaged given the occurrence of the natural phenomenon associated with a given intensity (hazard, Pe). Figure 1 shows the sequence starting from the occurrence of the natural phenomenon to the NaTech scenario.

To update dynamically the risk analysis, the Event Tree is used as causal reasoning of a Bayesian Network (BN) by which the NaTech Risk Index (RI) is defined. This index is the target node of the graphical model and represents a conditional probability of the occurrence of a certain potential of release and a specific damage (*D*), where the damage has been defined according on the classification of industries of the Seveso III Directive. The variable damage takes into account the amount of dangerous substances stored or handled inside the establishment, as well as the resident population included in the impact area of the NaTech scenario. Another needed variable in the BN is the category of population (Cat_n), it is used to group different typologies of non-resident people who may be in the impact area during the occurrence of the event.

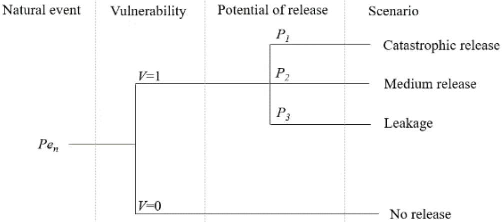

Figure 1 Sequence of the development of a NaTech scenario.

Figure 2 shows a graphical representation of the model used for the dynamic risk analysis as suggested in this work.

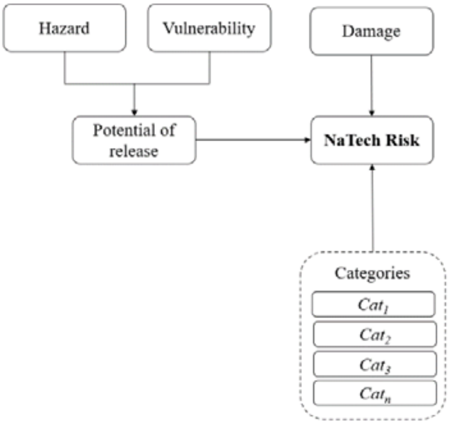

Figure 2 Graphical representation of the DRAN model.

The relationship between each variable (node) of the BN is defined by means oriented arcs. Each node has discrete states, criteria for the BN training allow describing the behaviour of a given node under the change of parent nodes. Therefore, the definition of the categories of population are used to update the *RI* for a certain geographic area. If no vulnerable population category is present, the NaTech risk index remains unchanged.

To apply the approach, data must be gathered. A geographical information system (GIS) has been developed to collected territorial data, e.g. population data, types of constructions included in the site, and industrial activities, as well as morphological characteristics of the territory (elevation, plains, slopes, etc.).

2.1. *Nodes of BN*

To develop the BN, the nodes must be defined. Firstly, the *hazard* (characterisation of the natural event) has been classified in three states:

- *Pe1* low probability of occurrence and high intensity.
- *Pe2* medium probability of occurrence and medium intensity.
- *Pe3* high probability of occurrence and low intensity.

The *vulnerability* node has two states, i.e. 0 or 1. It depends on the presence of the facility in the area, impacted from the natural event, and the exceeding of a threshold value of intensity (magnitude) of the natural phenomenon.

The *release* node relates the probability of occurrence of a given release magnitude and the probability and intensity of the flood it is defined as following:

- P_1: no. of plants exposed to flood hazard *Pe3*, i.e., a minor release of hazardous materials could be generated.
- P_2: no. of plants exposed to flood hazard *Pe2*, i.e., a medium release of hazardous materials could be generated.
- P_3: no. of plants exposed to flood hazard *Pe1*, i.e., a catastrophic release of hazardous materials could be generated.

The *damage* node is specified as:

- *D1*: lower tier establishments located in proximity of urban areas with a population density not exceeding 100 individuals per km^2 in the impact area.

- *D2*: upper tier plants located in proximity of urban areas with a population density not exceeding 100 inhabitants per km^2 in the impact area.
- *D3*: lower tier establishments located in proximity of urban areas with a population density exceeding 100 inhabitants per km^2 in the impact area.
- *D4*: upper tier plants establishments located in proximity of urban areas with a population density exceeding 100 inhabitants per km^2 in the impact area.

The *category* node refers to the presence of human beings (non-residents) in the impact zone of the NaTech. Three groups have been identified, which are associated with a given probability of a presence in the area. These are workers, students and hospitalised. Each of them is represented by an independent node with two states: 0 or 1 to indicate the presence of that category within a buffer zone of 1 km surrounding the establishment.

Finally, the *NaTech risk index* is composed of 4 states. *R1* represents the lowest risk value and *R4* is the highest. Its conditional probability table is given in Table 1.

Table 1: Conditional Probability Table of the Natech Risk node

Release	Damage	R
P_1	*D1*	*R1*
	D2	*R2*
	D3	*R3*
	D4	*R4*
P_2	*D1*	*R2*
	D2	*R2*
	D3	*R3*
	D4	*R4*
P_3	*D1*	*R3*
	D2	*R3*
	D3	*R4*
	D4	*R4*

2.2. *Criteria for the updating of the target node*

The Na-Tech risk index is updated by considering the presence of people in the buffer zone and using specific criteria for categorising the vulnerable population. If no vulnerable population is present, the risk index remains unchanged. Presence of Cat_1 (less vulnerable), increases the risk by one level, presence of Cat_2, increases by two levels, and Cat_3 (the most vulnerable), increases the risk by three levels.

3. Case study

The case study is represented by a large hydrographic basin crossed by a major river and hundreds of its tributaries. This basin covers a very large area (about 85,000 km^2). It includes a significant presence of industrial plants governed by the Seveso Directive, approximately 500. It can be observed that the case-study includes also thousands of other plants falling under the IPCC Directive (Directive 96/61/EC) on the integrated pollution prevention and control. Figure 3 shows the extension of the river basin and the location of the Seveso facilities.

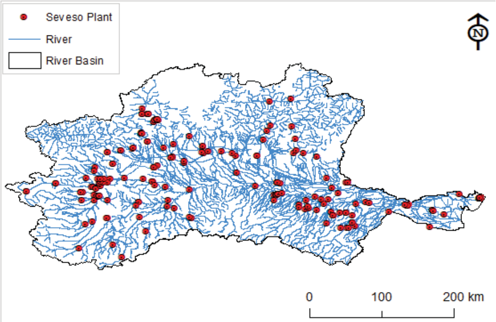

Figure 3. Extension of the river basin and Seveso establishments' location.

4. Results and discussion

The GIS allowed identifying the facilities within the flood risk areas (219) and among these, almost a third have been found to be upper tier establishments in compliance with current legislation. For each establishment, a conservative impact area with a radius of 1 km has been defined. The vulnerable elements present in the impact areas have been identified for the different hazardous scenarios of the flooding.

Figure 4 shows an example of the same impact area exposed to different flood hazards. It can be observed that several vulnerable elements, that are not involved by the natural phenomenon, can be potentially involved in the NaTech event.

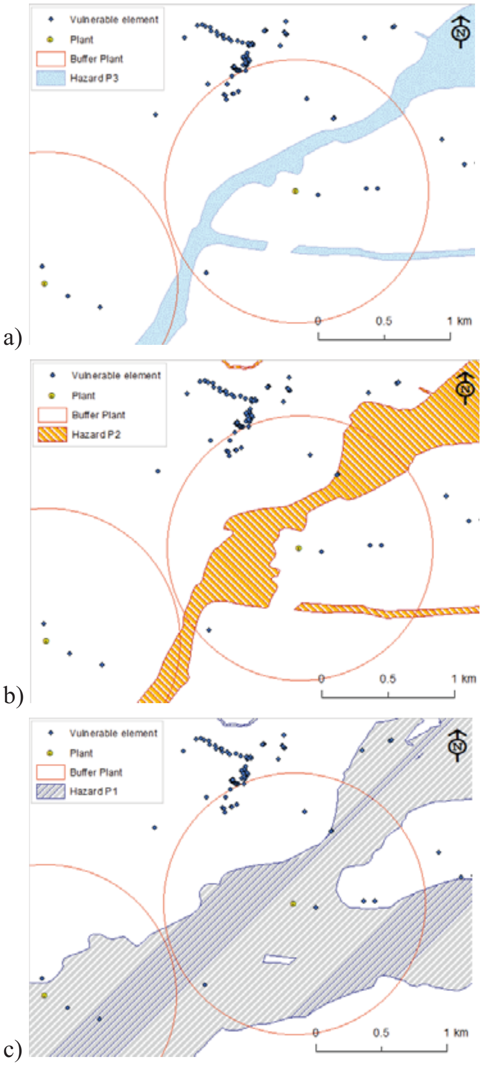

Figure 4 Impact areas of a NaTech due to different flood hazards: a) Pe_3; b) Pe_2; c) Pe_1.

The information extracted from the GIS query has been used to feed the BN. The categories of people group some sub-categories according to the probability of presence of individuals. Below a description is given:

- the first category of vulnerable elements collects workers (or assimilates) of public offices, pharmacies and clinics, cultural heritage, place of worship, etc. these have a presence in the area in the period from 08:00 a.m. to 08:00 p.m.;
- the second category refers to students from schools, university, nursery schools, college, banks, and their presence occur in the period from 09:00 a.m. to 04:00 p.m.
- the third category relates to hospitals with presence always constant (24 h).

The child nodes of the BN, i.e. the potential of release and the NaTech risk have been trained based on the criteria established above, while the parent nodes have been fed with the data obtained by means of the GIS analysis performed for the case study.

Figure 5 gives the obtained probability distributions, whereas Figure 6 shows the change of the probability distributions of the Target node when the evidence relates to the characterisation of the initiating event, i.e. the hazard is added, respectively due to a) an event with high probability of occurrence and low intensity; b) a rare event with high intensity.

This operation could be performed directly by the risk manager in real-time during the occurrence of the flood. In this way, he/she will be able to observe if the Risk is greater than expectations (obtained with a non-dynamic risk analysis) and what is the increase. Consequently, the manager will be able to implement mitigating actions more effectively and efficiently by optimizing the available resources.

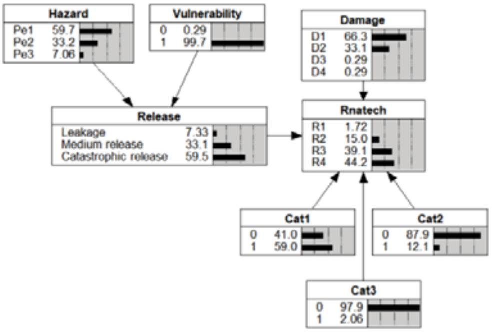

Figure 5. Probability distributions obtained with the criteria defined for child nodes and the real data from case-study.

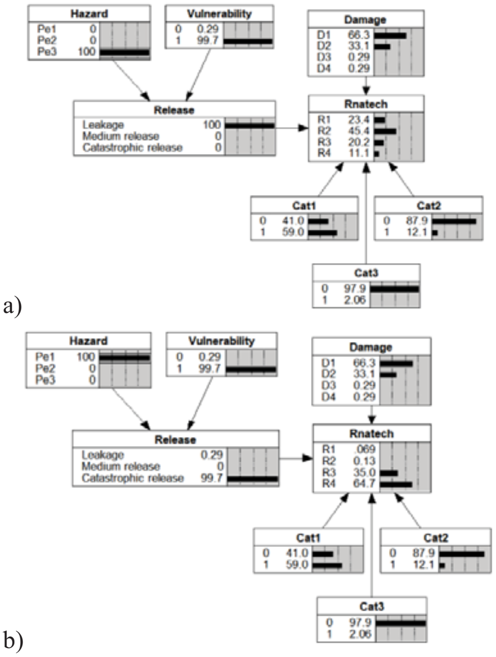

Figure 6. BN with evidence in the Hazard node, respectively a) Pe_3 and b) Pe_1

A further consideration is needed. The impact area depends on the type of substance, amount and related hazard, but in this case a circular buffer with a fixed (and conservative) radius has been used to obtain a conservative assessment that simplifies the analysis. However, it could be a limit given the variety of chemicals involved in the various establishments.

5. Conclusion

The proposed methodology, implemented in a GIS, provides a short-cut tool very useful for risk managers in assessing and managing NaTech. The severity of this type of scenarios is due to the possibility of affecting many people, whether they are inside the plant area (workers) or outside it (pedestrians). This means that the number of people potentially involved is not easily quantifiable. It certainly depends on the type of urbanisation surrounding the plant (e.g. rural area or inhabited centres including schools, public offices, commercial activities, etc. or residential areas). The identification the extension and location of the impact area of the potential NaTech event allows to better estimate the number of people present during the different time slots of typical day. As an example, in a residential area, it is expected to have a greater number of citizens at night, while in a commercial area, the presence of residents in the same time slot will be significantly lower, etc. It must be also considered that an extreme natural event can affect a large area, this means that several NaTechs can occur simultaneously, i.e. following the same natural event.

The purpose of the proposed tool is to help effectively and efficiently in managing the available resources to deal with the event during its occurrence. During an emergency, the risk manager can quickly activate proper measures in the area affected by the natural phenomena and by the presence of industrial plants at major accident hazard.

In summary, the update of the Na-Tech risk index is crucial in enhancing the accuracy of risk evaluation. Through the consideration of people in the buffer zone, potential hazards can be adequately assessed, and necessary preventive measures put in place, thus enhancing the safety of individuals and infrastructure.

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