Vulnerability Scenario Characterization in an Industrial Context using a Natech Indicator and a Territorial Multi-risk Approach

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Vulnerability Scenario Characterization in an Industrial Context using a Natech Indicator and a Territorial Multi-risk Approach.

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A growing number of natural hazards triggering technological accidents (Natech) has been duly reported from all around the world. However, the multi-hazard and multi-stakeholder character governance of Natech risk is challenging, it requires a comprehensive territorial approach to elucidate the possible simultaneous scenarios and to address the protection of industrial installations and their possible safety-relevant interactions with neighboring critical infrastructures, environment, and communities. Consequently, the goal was to establish a protocol for the vulnerability characterization between the mutual interdependencies of the industrial and the surrounding multi-risk contexts where the industry is located. A previously validated Natech Indicator was implemented as an early warning system, while a multi-risk tool previously validated, was used for the territorial vulnerability characterization in case of an alert. Spatial analyses using the Geographical Information System (GIS) were developed from multiple indicators nested in a systemic vulnerability index, represented on a homogeneous grid. Risk scenarios were generated for the industrial context of interest highlighting the vulnerability to suffering disruptions from natural hazards and pressures. The results showed that industrial infrastructures might represent a double territory threat, one regarding their technical characteristics and hazardousness, and the other when their technological items collide with natural hazards and territorial stressors and provoke cascading events. In addition, the results increase the awareness of the industrial operators and the planners regarding a set of vulnerabilities only rarely analysed holistically. Consequently, this approach may contribute to enhancing the preparedness of risk governance and risk reduction, of both industries and territories. Further research is required to implement this approach in different industrial contexts addressing the time course of natural disruptions, within a framework to increase resilience.

Keywords: GIS, Natech, natural hazards, multi-risk, vulnerability.

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1. Introduction

In the past, chemical plants were perceived as standalone facilities that produced chemicals and other products in isolation. However, with the development of technology and increased awareness of environmental and sustainability issues, the industry has evolved to a more integrated and holistic approach (Prerna et al., 2017). Therefore, chemical industries are no longer perceived as isolated facilities, but as part of larger, interconnected socio-ecological and technological systems (SETSs), that consider the entire production process and its impacts on human beings and the environment.

In this context, the Seveso III Directive (2012/18/EU) aims to prevent, prepare for, and respond to major industrial accidents involving hazardous substances, to protect human health and the environment. The directive sets out requirements for the classification and labelling of hazardous substances. Then, operators of these establishments must identify, manage the risks associated with these hazardous substances, and submit a “safety report”, which contains the scenarios that the operator regards as credible (often referring to top events with a likelihood greater than 10^{-6} times per year). Subsequently, regulators must review all safety reports and verify their compatibility in the territories (European Commission, 2012).

The Seveso safety reports are good practice and contribute to standardize the information and the classification of hazardous substances and fostering the introduction of lessons learnt from past accidents. However, there remains a need to integrate all the safety reports generated on the municipal and regional scales from a systemic approach, associated with other risks, the urban dynamic, and its trends over time and space (Castro Rodriguez et al., 2022).

For instance, new challenges faced by people involved in disaster risk management are the so-called high-impact and low-probability events (HILP), such as technological events triggered by natural hazards (Natech). Even if this kind of event presents a small likelihood (often neglected by operators), in case of occurrence, it may cause severe damage to individuals, infrastructure, environment, and society, being particularly complex because often it is the result of cascading events (Mesa-Gómez et al., 2020). Furthermore, there is some evidence suggesting that an increasing in the frequency of certain types of Natech, may be linked to climate change (Ricci et al., 2021). It could deeply modify the foreseen expected frequency for Natech events.

Despite natural risks being an important consideration within the Seveso III Directive, nature, and the environment are often considered target components. The inverse complex interaction where the industrial facilities should be seen as targets infrastructure of natural hazards is typically not explored in sectorial risk plans or overlooked due to its perceived low probability (Pilone et al., 2021).

Moreover, the Sustainable Development Goals (SDGs) issued in 2015 for the United Nations Agenda, highlight the necessity of developing holistic risk management approaches in all sectors, to strengthen the resilience and the adaptive capacity to the different natural hazards and disasters, in line with the Sendai Framework for Disaster Risk Reduction 2015–2030 (United Nations, 2015a; 2015b). Accordingly, it is necessary to adopt new instruments that must radically differ from what has been adopted so far, integrating engineering risk management tools with the interdisciplinary historical perspective at a local scale (Brunetta and Salata, 2019).

With these premises, the purpose was to establish a protocol for the characterization of the vulnerability between the industrial site and the surrounding multi-risk contexts where the industry is located.

These first attempts use a hypothetical case study with elements from the real world, to systematize how a smooth integration among the management of industrial and natural hazards could increase the vulnerability awareness which result a central issue to strengthen the resilience of both establishments and the territories.

2. Case Study

The hypothesized Seveso establishment corresponded with a typical industrial typology clustered in the macro-sector “Power production” according to the description given by Casson Moreno et al. (2018). Its specific activity is the power production from the combustion of hydrocarbons. The unitary operations that are carried out in the plant are both chemical and physical. The activities also include auxiliary technical systems necessary for the production plant's operation, such as compressed air, treated wastewater, steam production, and warehousing. Within all the processes and functions of the plant the following items were identified: atmospheric storage tanks, tall structures such as chimneys and process columns and equipment, heat exchangers, complex systems of pipelines, complex electrical networks, and water treatment organs.

The installation belonged to a Nord Italian municipality of approximately 50,000 inhabitants close to one of the country's main cities. At a morphological level, the territory can be distinguished between a hilly and a flat area crossed by a variety of watercourses including rivers, creeks, and artificial channels. The hillside area consists of a higher-altitude zone covered by woodlands and a lower-altitude area of urbanized terrain on which the historical settlement is located. Later urban expansions and the establishment of industries and manufacturing activities expanded in the lowlands along the water courses, consolidating in some positions with the conurbation of the near city. The settlement has a prevalent industrial character and is intersected by important routes and railways.

3. Procedure

Since the chemical plants are highly heterogeneous in terms of productive macro-sectors, technology, hazardous substances detained, and different geographical realities where they are located, the failure modes caused by natural hazards may result in different loss of containment (LOC) scenarios. Therefore, it is crucial to develop in-deep analysis including the principal interdependencies among the hazardous substances detained, the most critical industrial items, and the related territorial hazards. Regarding this issue, the subsequent subsections described the protocol adopted as methodology.

3.1. *Natech Early Warning System*

A Natech indicator previously validated by Pilone et al. (2021) and Pilone et al. (2022) was implemented. It consists of a simplified semi-quantitative initial assessment of Natech used as an early warning system. This indicator can be helpful to decision-makers dealing with vulnerabilities of NaTech that threaten both, human health, and the environment.

In a nutshell, this method intersects information among the natural hazards that threaten the area where the plant is located, their interaction with the industrial vulnerable items (Factor A), and the hazardous substances involved in the plant (Factor B). The data needed for implementing this method could be collected from the safety report in the case of Seveso establishments (case addressed hereinafter). Furthermore, process site inspections, audits, environmental information, and questionaries could be suitable for collecting the information (Castro Rodriguez et al., 2021a; 2021b), resulting in crucial cases of non-Seveso facilities where the compilation of safety reports is not mandatory.

3.1.1. *Factor A*

For the verification of Factor A, the presence and the position of diverse categories of industrial equipment must be identified. Regarding this, the chapter “establishment description” in the safety report, constitutes a cornerstone, where the technology, the process, and the operating conditions are described.

On the other hand, for the identification of natural hazards the “presentation of the establishment site” in the safety reports may be consulted. From this, it is possible to identify important elements such as the establishment description and its territorial location, its geographical position, as well as meteorological, geological, seismic, and hydrographic information. The latter association should follow the typical damage modes triggered by the natural hazards described in the “guidance for operators of hazardous industrial sites and national authorities” (European Commission, 2022). Then, the interaction between vulnerable items and natural hazards was preliminarily evaluated following the binary criteria proposed by Pilone et al. (2021, 2022).

3.1.2. *Factor B*

Factor B is divided into two sub-factors related to the Type (B1) and Quantity (B2) of each hazardous substance detained by the plant. For instance, B1 depends on the section within Annex I of the III Seveso Directive to which the substance corresponds (such as sections H, P, E, O) (European Commission, 2012).

Furthermore, B1 was split into two sub-categories, according to the dimensions of human health (B1HH) and environment (B1Env). Consequently, B1HH associate ranks for substances in the sections human health (H) and physical hazards (P) from the above-mentioned Annex, while different ranks are assigned to B1Env which includes substances in the section hazardous to the environment (E), and other substances (O). On the other hand, the ranks assigned to B2, depend on substances trespassing or not the thresholds (upper-tier, lower-tier) declared for any category inside the principal sections of Annex I of the III Seveso Directive. In addition, 20% of lower-tier thresholds were included in the assignation of ranks, in line with regional legislation (DGR, 2010). More details about the steps to calculate the factors and the ratings assigned can be found in previous research (Pilone et al., 2021; 2022).

3.1.3. *Natech Indicator determination*

Summarizing, the Natech Indicator (NI) is estimated according to Eq. (1):

$$\mathrm{NI} = \mathrm{Factor\ A} \cdot \sum_{j=1}^{m} \frac{1}{n_m} \sum_{i=1}^{n_m} (\mathrm{Factor\ B1_i} \cdot \mathrm{Factor\ B2_i}) \qquad (1)$$

where,

m: corresponds with consecutive integer values assigned to each sequential section within Annex I of the III Seveso Directive (H=1, P=2, E=3, O=4, and other substances).

n: corresponds to the number of different substances detained inside the same *m*-section.

3.2. *Territorial Vulnerability*

The preceding indicator constitutes an overall warning to understand, in terms of magnitude, the Natech potential corresponding to the information available in safety reports. However, in case of alert, the specific predisposition of the industrial context to dangerous phenomena should be deepened, to cope with the cascading events which may harm the environment and the surrounding population and incorporated into the emergency plans. Consequently, the multi-risk tool proposed by Beltramino et al. (2022), to determine vulnerabilities at the local scale, offer an interesting application to this context. The previously mentioned tool consists of a mathematical framework to determine the systemic vulnerability at the municipal scale, integrating multiple indicators clustered into three factors defined as sensitivity, pressures, and hazards, weighted according to a participatory procedure. These multiple indicators are nested in layers onto a grid of homogeneous cells (200 x 200 m) which covers the municipality combining all the relationships and elements examined and allowing an overall reading of the critical territorial aspects. The principal output is a colored map suitable to reading by non-experts, representing the systemic vulnerability through an ordinal scale of four categories (Low-green, Moderate-yellow, High-orange, and Critical-red). More details of the methodology may be found in Beltramino et al. (2022).

Furthermore, the potential disaster areas in case of major accidents (exclusion and observation areas) were applied as buffer zones surrounding the establishment (Castro Rodriguez et al., 2022). The specific distances applied to the observation and exclusion areas were selected considering the specific information about the characteristics of the hazardous substance (DGR, 2010).

For the specific analysis of the industrial Natech scenarios, the values of the systemic vulnerability Index (IVS) were focused on the corresponding cells of the grid where the plant is located and its surrounding territory. Subsequently, an inverse analysis was carried out where IVS was broken down into its main components up to the pressure and hazards able to impact the industrial context. Spatial analyses using Geographical Information System (GIS) were developed to individuate each scenario. The vulnerability of each indicator within the IVS belongs to the range [0;1], which represents the increase in vulnerability when the index is close to 1 and vice versa. The color scale was based on the natural breaks classification method, so it differs from the colors of the IVS.

4. Results and Discussion

Since the limited space and the complex methodology, the sequential development of the procedure will be presented in a simplified way, adopting some assumptions for a better illustration of the methodology potentials applied to this theoretical case.

4.1. *Early Warning System Implementation*

This section presents and discusses sequentially the passages to determine the Natech indicator from the information available in safety reports.

4.1.1. *Factor A*

To simplify the case study, neither "underground deposits" nor "hazardous storages" were considered vulnerable industrial items. Along the same line, the storm was neglected from the natural hazard. Table 1 presents the determination of factor A under the conditions hypothesized (in this case all the items considered are outside).

4.1.2. *Factor B*

Table 2 summarizes all the information related to the hazardous substances involved in the plant, with the ratings for the factors Type and Quantity.

Table 1. Rating of the vulnerable items vs. natural hazards (Factor A).

Vulnerable Items →	**Water treatment basins**	**Storage tanks**	**Underground deposits**	**Tall structures**	**Basins / Process equipment**	**Hazardous Storage**
Hazards ↓	X	X	not present	X	X	not present
Earthquake	1	1	0	1	1	0
Flood	1	1	0	0	1	0
Storm (not considered)	0	0	0	0	0	0
Fire	0	1	0	0	1	0
Obsolescence	1	1	0	1	1	0
Total ratings	3	4	0	2	4	0
Factor A=13						

Table 2. Hazardous substances are involved in the Seveso plant.

2012/18/EU Annex I section	**Hazardous substance**	**Hazard Statements**	**Upper tier threshold (t)**	**20% of lower tier (t)**	**Quantity (t)**	**B1HH**	**B1Env**	**B2**
Environmental Hazards (E1)	Dense Fuel-Oil BTZ	H410, H226, H350, H315	200	20	20000	-	3	1
Physical Hazards (P5c)	Automotive Diesel	H226, H315, H332, H351	25000	500	100	2	-	0.2

From the simple observation of the table, it can be appreciated not only the substance's dangerousness (consult hazard statements) but also how the upper-tier threshold is extensively surpassed for Dense Fuel-Oil BTZ. With the information obtained in 4.1.1 and 4.1.2, the Natech Indicator is determined in the next step.

4.1.3. *Natech Indicator determination*

This section presents the final determinations for both NIs, that is for human health (HH) and for the environment (Env). In Eq. (2) and Eq. (3) is shown the final solution.

$$\mathrm{NI(Env)} = \mathrm{FactorA} \cdot \left(\frac{\mathrm{B1_{E1}} \cdot \mathrm{B2_{E1}}}{1}\right) = 13 \cdot \left(\frac{3 \cdot 1}{1}\right) = 39 \qquad (2)$$

$$\mathrm{NI(HH)} = \mathrm{FactorA} \cdot \left(\frac{\mathrm{B1_{P5c}} \cdot \mathrm{B2_{P5c}}}{1}\right) = 13 \cdot \left(\frac{2 \cdot 0.2}{1}\right) = 5.2 \qquad (3)$$

In the case of NI(HH), no significant alarm resulted, as the value obtained is around 3% of the highest NI(HH) value. Conversely, NI(Env) represents approximately 37% of the potentially highest value. In consequence, the detainment of Dense Fuel-Oil BTZ and its potential interaction with external factors, generated an alarm for the decision-makers about the susceptibility of the plant, to suffer disruptions able to generate cascading events, which may considerably harm the environment directly, but also the population, according to the hazard statements of the substance and its potential top events.

4.2. *Territorial Vulnerability Representation*

Figure 1 shows the IVS for the area of interest.

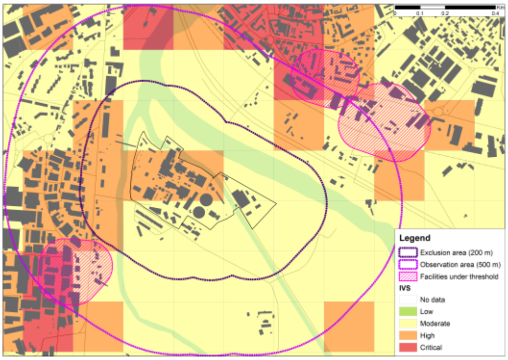


Fig. 1. IVS for the industrial context of interest.

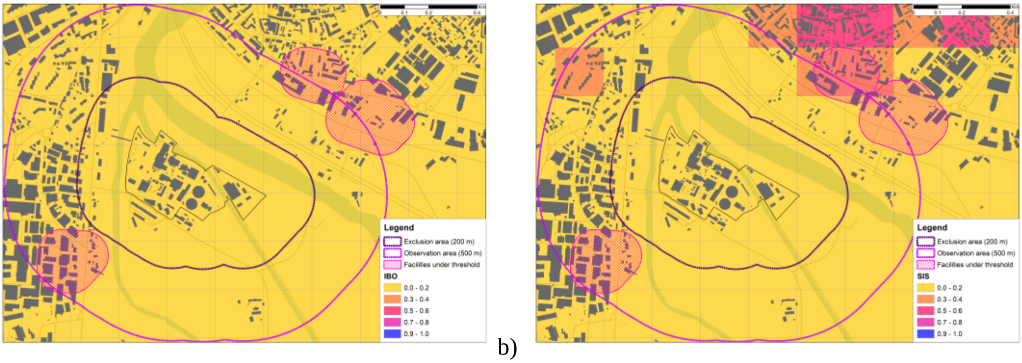
The area of interest was selected from the vulnerability analysis at the municipal scale discussed in Beltramino et al. (2022). It comprehended approximately 280 hectares and conformed of 70 exhaustive homogeneous cells. It corresponds to an industrial context that not only includes the plant inside the fence, but also the entire environment with which the facility interacts.

The systemic vulnerability analysis according to the visual field yielded approximately 65% of the cells with moderate vulnerability (yellow), 26% with high vulnerability (orange), and 9% with critical vulnerability (red). It is important to remark that the few critical vulnerability cells corresponded to areas that only partially intersect the observation area (farther than 500 m). In contrast, within the perimeter of the plant, more than 50% of the occupied area is found with a coloration corresponding to high vulnerability, while another 3 orange cells are included within the exclusion area in case of a major accident occurred.

In addition, it can be also appreciated how different binding areas applied to other neighbor plants may interact with the observation area, being able to cause domino effects. Therefore, the zone analyzed is highly vulnerable to the mutual interaction between both industrial and external hazards, susceptible to suffering cascading events that may harm the environment, the population, and the infrastructure.

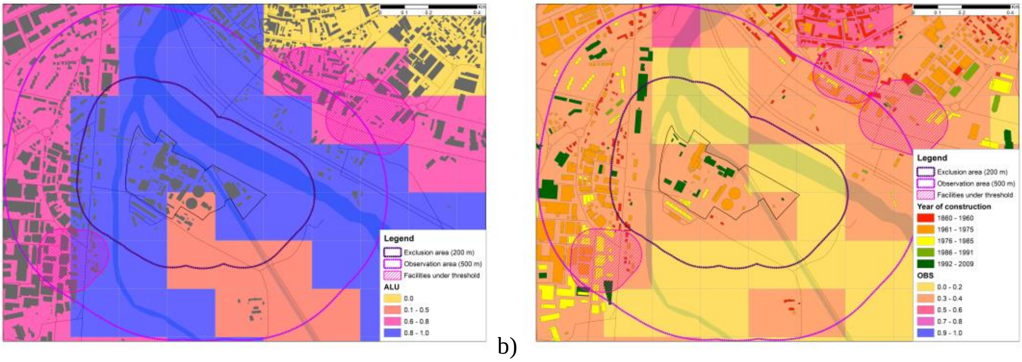
In this line, a components breakdown for IVS was carried out up to the pressure and hazards able to impact the industrial context.

Regarding the breakdown, this section just highlighted the contrast between the less relevant and the significative hazards used to determine Factor A (see Table 1). Then, Figure 2 starts to illustrate the vulnerability representation of two natural hazards which were not considered significant to the industrial context.



a) b)

Fig. 2. Vulnerability representation of natural hazards not significant to the industrial context. a) Wildfires (IBO). b) Earthquakes (SIS).



a) b)

Fig. 3. Vulnerability representation of natural hazards and pressures significant to the industrial context.

a) Floods (ALU). b) building obsolescence (OBS).

Even if both hazards, earthquakes, and wildfires were assigned the binary rate 1, in subsection 4.1.1, it can be appreciated from a deeper analysis that, although they should not be completely disregarded, the industrial context vulnerability against these hazards is low.

On the other hand, Figure 3 presents a vulnerability representation of significant hazards and pressures. Looking at Figure 3a, it is not difficult to note how practically all the cells in the exclusion area, including those in the internal perimeter of the plant, are critically vulnerable to the impact of floods. The rest of the visual field in the industrial context alternates between critical and high vulnerability. The potential impact of this natural hazard is conditioned by the proximity of the plant location to the bed of a river which bifurcates on both sides of it. According to the European Commission (2022), this kind of natural hazard may trigger several damaged modes to industrial items such as buckling, rupture of pipes and connections, overfilling of process equipment, displacement and overturning of structures, and pushed objects against the equipment provoking the puncturing phenomena.

Moreover, Figure 3b shows buildings obsolescence as a linear and generalized trend that affects gradually the industrial context cells. In addition, it is important to note how the punctual elements in the plant area are categorized according to the year of construction. From this, it can be perceived that some process areas and the round structures corresponding to storage tanks had more than 50 years of construction. Then, a specific analysis should be done as proposed by Milazzo and Bragatto (2019).

5. Conclusions

From the methodological point of view, this research initially proposed a protocol from the available information on the Seveso safety reports, implemented as an early warning system. Depending on the Natech alarms, a spatial multi-risk vulnerability analysis was adapted to the industrial context, and the breakdown of the indicators was done to identify the incidence of the specific hazards and pressures of the system.

This protocol was tested in a hypothetical case study, with an industrial context comprising urban and natural elements. It raised an alarm for the stored substance Dense Fuel-Oil BTZ regarding the potential environmental impact. The vulnerability analysis subsequently resulted in a high systemic vulnerability in the analyzed industrial context, with the specific interaction between the hazardous detained and the risk factors of flooding and obsolescence being the most significant in the analysis.

The results increase the decision-maker awareness of the vulnerability characterization between the mutual interdependencies of the industrial plants and their surrounding multi-risk contexts allowing an interdisciplinarity evaluation.

6. Recommendation

Further research is required to improve the weighted association between industrial items and multi-risk factors. Furthermore, quantitative risk assessment methodologies should be integrated for specific vulnerable resulting items.

The proposed method must be integrated into a framework which starting from this characterization of the industrial context vulnerabilities, enables to develop the system preparedness and recoverability in case of disruption, strengthening in this way both industrial and territorial resilience.

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