Multi-risk NaTech vulnerability indicator: A step further

Journal of Loss Prevention in the Process Industries 95 (2025) 105588

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

"Multi-risk NaTech vulnerability indicator: A step further"

David Javier Castro Rodriguez *, Antonello A. Barresi, Micaela Demichela

Department of Applied Science and Technology, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy

ARTICLE INFO

Keywords:
Critical infrastructures
Leading indicator
Multi-risk
NaTech
Vulnerability

ABSTRACT

NaTech events involve technological disasters triggered by natural hazards, leading to hazardous material releases. Their multi-risk nature necessitates comprehensive vulnerability assessments to enhance system preparedness. This research presents a further step towards a multi-risk NaTech vulnerability assessment for industrial plants, refining a previous methodology with reference to a case study. A wide flexible selection of natural hazards is proposed, emphasizing the need for a "location priority factor" that considers hazard spatial influence, the conditional probability of NaTech events based on industrial macro-sectors, and cascading effects between hazards. Additionally, interactions among neighboring infrastructures are introduced as an extra hazard factor. To ensure consistency with prior research and historical NaTech data, a broader set of harmonized industrial item categories is defined. The study highlights the dynamic vulnerability of critical items within a plant, considering their layout proximity and functional interconnections. Moreover, multi-risk assessment is improved by integrating quantitative criteria for ratings derived from historical NaTech analyses. An enhanced index for assessing major industrial accident potential based on hazardous substance criteria is proposed in alignment with European legislation. The proposed decision matrix combining independent evaluations of infrastructure and substance-related factors may support risk assessment through varying levels of tolerance, guiding preparedness strategies for industrial systems.

1. Introduction

In the report on the implementation of the European Union (EU) strategy on adaptation to climate change, the European Commission acknowledged that if the current trends in climate change keep going, the critical infrastructures in Europe would experience a huge increase in annual damage by the end of the century, with industry being among the sectors with higher losses (European Commission, 2018a). Seeking to improve resilience by preparing all government levels to respond to climate change, the European Commission has released Directive (EU) 2022/2557[1] to strengthen the resilience of critical entities. This Directive requires that Member States identify critical entities and evaluate the risks associated with them by establishing a national strategy by January 2026, to ensure resilience. Based on this evaluation, critical entities should adopt the relevant organizational and technological steps to guarantee their resilience, taking into consideration all relevant natural and man-made hazards that might be translated into undesired losses. Moreover, this directive establishes in Article 5 that, when Member States conduct risk assessments, those must be conducted in compliance with the requirements of the applicable sector-specific European Union legislation, such as 2012/18/EU.[2]

Currently, Seveso III (2012/18/EU) plays a key role in directing the European Union towards achieving zero pollution resulting from industrial accidents, as specified in the European Green Deal and Zero Pollution Action Plan (European Commission, 2021). Then, there is a clear intention to align the Seveso III directive more closely with international policies and strategies. This intention serves as an overarching framework that encompasses concepts that the Seveso III directive has either not incorporated or has not sufficiently evolved to address, given that its last update was in 2012. For instance, the necessity to strengthen resilience and adaptive capacity to different natural hazards and inherent disasters is explicit within the framework of the 2030 Agenda for Sustainable Development (United Nations, 2015). Additionally, the Sendai Framework for Disaster Risk Reduction

* Corresponding author.
E-mail address: david.castro@polito.it (D.J. Castro Rodriguez).

[1] Directive 2022/2557/EU of the European Parliament and of the Council on the resilience of critical entities and repealing Council Directive 2008/114/EC.

[2] Directive 2012/18/EU on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC.

https://doi.org/10.1016/j.jlp.2025.105588
Received 4 December 2024; Received in revised form 7 February 2025; Accepted 9 February 2025
Available online 11 February 2025

2015–2030 emphasizes the importance of multisectoral integration in multi-hazard comprehensive studies. These studies should incorporate assessments, mapping, monitoring, and early warning systems for multiple hazards. This framework also advocates for reviewing the coherence of these approaches with traditional methods to achieve the goal of minimizing losses in lives, livelihoods, and health (UNDRR, 2015).

However, when considering the potential impact of natural causes, the 2012/18/EU Directive is limited to mentioning that companies under Seveso III must detail in their safety reports the description of major accident scenarios related to these causes, exemplifying just earthquakes and flood factors. Other potential NaTech events — technological scenarios involving the release of hazardous materials caused by a natural hazard (Krausmann et al., 2017) — are not mentioned within this legal text. Moreover, it is of great concern that NaTech scenarios are often underestimated by operators under the current methodology for the identification of risk inventories (Reniers et al., 2018) because the likelihood is considered negligible. In contrast, some evidence indicates a higher incidence of NaTech in Europe during the last two decades, with not neglectable average frequency (Ricci et al., 2021).

Regardless of the increment in the likelihood trend of NaTech in Europe, these events should not be underestimated due to the severity of their potential consequences. NaTech events are regarded as high-impact, low-probability (HILP) scenarios (Paltrinieri and Reniers, 2017). These events can lead to a loss of containment (LOC) in industrial facilities storing or handling hazardous materials, potentially causing catastrophic harm to people, infrastructure, environment, and society, if they occur. NaTech events have the potential to not only trigger short-term undesirable events but also result in long-term consequences for industrial infrastructures, including plant shutdowns, business interruptions, and loss of critical supply infrastructures (Mesa-Gómez et al., 2020).

Antecedents exist of an evaluation of risk management progress conducted by the European Commission (2018b) which measured natural hazards through a set of 11 indicators and sub-indicators; they delved that fewer than 10 Member States considered NaTech events within the industrial sector. Regrettably, among the few Member States addressing the impact of natural hazards, many restricted their responses to sector-specific programs issued by diverse authorities, often using different methodologies and scales (Krausmann and Baranzini, 2012; Pilone and Demichela, 2018).

Decision-makers usually assess natural hazards separately, often using outputs of methodologies incompatible among them. They lack holistic tools to analyze systemically multiple factors, which are particularly complex due to their frequent cascading and escalation events (Mesa-Gómez et al., 2020). Additionally, the use of traditional approaches for ordinary operational safety at plant scales, which lack information about the magnitude and frequency of multiple natural factors (Reniers et al., 2018), leads to inadequate management of NaTech events across all process industries. Although several methodologies based on multi-risk approaches are available in the literature (Gallina et al., 2016), most of them are primarily focused on the assessment of hazards in urban areas, overlooking the technological perspective. The few multi-risk approaches that consider NaTech hazards are either too general to be effective at the plant level (Pilone et al., 2016) or fail to address the specific functional aspects of industrial plants, such as the vulnerability of different equipment items and the quantity and type of dangerous substances stored (Mesa-Gómez et al., 2020).

Only recently researchers have considered holistic approaches from a multi-hazard and multi-stakeholder perspective, including the facilities and their overlapping local risks, both on-site and off-site (Suarez-Paba and Cruz, 2022). In this line, Pilone et al. (2021) have introduced a simplified NaTech indicator, consisting of a pre-screening metric for the potential NaTech vulnerability estimation from a multi-risk point of view. Although this tool was designed as an easy-to-use indicator for local planners, it represented an initial effort to integrate multiple hazardous factors impacting various types of industrial items at the plant scale. Furthermore, it introduced a factor to assess the vulnerability of plants based on the hazardous substances they contain, thereby completing the multi-hazard framework within the NaTech concept.

The present research critically discusses the simplified methodology for determining the NaTech vulnerability potential of industrial plants, previously proposed by Pilone et al. (2021), in order to identify opportunities for its enhancement. The outcomes will contribute to filling in the gap underlined by Jain et al. (2017) regarding the absence of leading indicators in the Seveso III Directive. Specifically, the conceptual ideas stressed here represent a step forward in assessing the NaTech potential of specific industrial establishments anticipating multiple natural disruptions. This approach helps raise awareness of the multidimensional interplay between technological factors within industrial plants and the multiple hazards inherent to their location, which is a cornerstone for enhancing system preparedness for future NaTech events.

2. Theoretical section on NaTech and multi-risk assessment

NaTech risk assessment has gained attention among scholars in the last decades, and its state-of-the-art can be broadly categorized into qualitative and quantitative methodologies. Qualitative or semi-quantitative risk assessment has helped to identify the potential hazards and consequences of natural disasters on technological systems by incorporating historical data and scenario analysis. This approach leverages expert knowledge and insights that may not be easily quantifiable, enabling a more nuanced understanding of complex interdependencies. For instance, Cozzani et al. (2010) conducted a historical analysis of industrial accidents triggered by flood events, while Renni et al. (2010) carried out a similar study focused on lightning. Krausmann et al. (2011) expanded the scope by adding earthquakes to the flood and lightning analysis, establishing key lessons learned regarding industrial vulnerability to these three natural hazards. More recently, Ricci et al. (2023a, 2023b) conducted historical analyses of NaTech events linked to extreme temperatures, including both cold and heat waves. Additionally, Ricci et al. (2021) took a comprehensive approach analyzing Na-Tech events caused by various natural factors, using data from European and American databases, while a similar study was conducted by Gao et al. (2023) using Chinese databases.

On the other hand, quantitative risk assessment (QRA) uses mathematical models, statistical studies, and simulations to quantify the likelihood of NaTech occurrences and their possible effects on industrial assets. These techniques offer a structured, reproducible, and often probabilistic understanding of risks, facilitating a more objective risk assessment by providing specific insights into the magnitude of potential repercussions and the effectiveness of mitigation strategies. Prominent researchers in the process industry have significantly advanced the understanding of how natural hazards can trigger technological disasters through the development of quantitative frameworks. For example, Salzano et al. (2003) assessed the seismic risk of atmospheric storage tanks within the framework of QRA. Subsequently, Antonioni et al. (2007) developed a methodology for the QRA of major accidents triggered by seismic events, later extending its scope to NaTech scenarios caused by floods (Antonioni et al., 2015). Moreover, Cozzani et al. (2014) introduced QRA approaches for domino and NaTech scenarios in complex industrial areas. Additionally, Necci et al. (2016) applied QRA to major accidents triggered by lightning, while Misuri et al. (2020) focused on domino effect scenarios caused by this specific natural phenomenon. Furthermore, specific research has been conducted to develop vulnerability models for equipment exposed to natural hazards (Caratozzolo et al., 2022). However, most research efforts to date have primarily concentrated on understanding the dynamics and estimating the consequences of individual natural hazards.

In this context, the authors considered that NaTech risk assessment in general should move towards integrated methodologies that combine qualitative and quantitative approaches to deliver full and actionable evaluations. Furthermore, the merging of Geographic Information Systems (GIS) and remote sensing technologies has improved the capacity to spatially model natural threats, yielding not only useful insights for emergency management (Luo et al., 2021, 2022) but also the spatial vulnerability profile of the industrial infrastructure to multiple hazards in their territories (Castro Rodriguez et al., 2025a).

NaTech occurrences possess unique characteristics that set them apart from other kinds of technological events. Inadequate awareness and poor levels of preparedness can significantly hinder the efficiency of current risk management strategies in mitigating NaTech events (Necci and Krausmann, 2022). In addition, contrary to common belief, NaTech events can also be triggered by "minor" natural hazards (Krausmann and Baranzini, 2012). Therefore, multidisciplinary collaboration becomes important, needing insights from engineering, environmental science, urban planning, and social and legal sciences.

Following the idea stated in Pilone and Demichela (2018), the NaTech events can be understood as a peculiar type of multi-risk, where an external natural hazard activates a technological one. Moreover, the original triggering factor can be split into single or multiple perspectives, depending on whether the foreseen technological scenarios are caused directly by one natural hazard or due to cascading events among more than one hazardous factor.

For a better understanding of the multi-risk concept, two important pillars are the "multi-hazard" and the "multi-vulnerability" concepts, including their possible interactions (Gallina et al., 2016). The idea of a multi-hazard is defined as a mix of two or more threat factors that can happen separately, at the same time, or in a chain reaction to cause a disaster. These events can be caused by one or more natural factors (Mesa-Gómez et al., 2020). Multi-vulnerability, on the other hand, may consider various exposed elements with potentially different sensitivity degrees to the various types of hazards considered (Gallina et al., 2016).

Multi-risk analysis aims to evaluate the spatial distribution of various hazard effects as they overlap on the vulnerable target of interest. It estimates their impact using either probabilistic or deterministic methods, aiming to make different risks comparable (Liu et al., 2015), where two trends are mainly considered to address the previous concepts.

On the one hand, the hazard sources in a region are usually harmonized by applying probabilistic assessments representing a set of discrete events in a reference time interval or even using experts judgment (Marzocchi et al., 2012; Necci and Krausmann, 2022). The results are presented as single-hazard maps, and superposed layers maps (Beltramino et al., 2022). On the other hand, methodological multi-risk approaches which employ mathematically rigorous methods to calculate risk interaction probabilities are also used. However, it is widely recognized that uncertainties and shortcomings can significantly impact these methods (Marzo et al., 2015).

One crucial aspect involves defining a common metric to assess losses and weigh the exposed elements based on the various impacts of hazardous events. Therefore, even well-structured theoretical mathematical frameworks necessitate simplifications due to the extreme difficulty in obtaining detailed information (Liu et al., 2015). In this regard, the introduction of semi-quantitative methods offers a convenient solution using rating-based systems (RS) (Suarez-Paba and Cruz, 2022), common to all the main risks (Pilone and Demichela, 2018).

3. Initial multi-risk attempt to assess the NaTech vulnerability at plant scale

The multi-risk method proposed by Pilone et al. (2021, 2022) for assessing NaTech vulnerability potential is based on a simplified ex-ante indicator designed for local planners. This method cross the ratings given to the exposure of various industrial items (multi-vulnerability) to a set of multiple hazards, with a factor derived from the quantity and hazardousness of the stored dangerous substances. Fig. 1 illustrates the theoretical conception of this method from a multi-risk perspective, aligned with the key conceptual elements of the NaTech concept as defined by Krausmann et al. (2017).

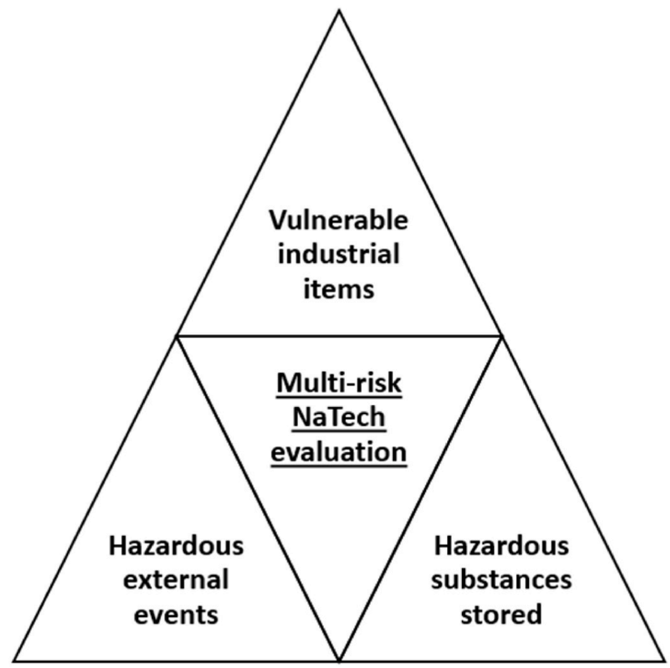

Fig. 1. Theoretical conception of the multi-risk NaTech vulnerability indicator.

This section introduces the initial version of the multi-risk NaTech vulnerability indicator; it is divided into two main parts: a general methodological description and its implementation in a case study.

3.1. *Methodological description of the simplified NaTech vulnerability indicator*

Beforehand, the NaTech questionnaire proposed by Pilone and Demichela (2020) can be used to collect the necessary information. The questionary is composed of three main sections that acquire data about: i) storage methods and exposed industrial equipment according to the plan technology; ii) description of eventual past accidents that occurred in the plant; iii) premises to prevent environmental impacts. This questionnaire can be completed using the information in safety reports or audits if available. Otherwise, interviews, direct observation, and elaborations based on plant documentation and field work are key aspects of gathering the required data as detailed in previous research (Castro-Rodríguez et al., 2020). Once that the required data is available the determination of the simplified NaTech vulnerability indicator consists of three main steps that are subsequently described: *Factor A*, *Factor B*, and calculation.

3.1.1. *Factor A*

Factor A estimates the interaction between a predefined cluster of industrial items categories and a set of hazardous factors that may threaten the plant location. Below are the industrial items and hazards considered by the method, to characterize the infrastructure vulnerability in each location.

Industrial items: a) basins for water treatment; b) storage tanks (atmospheric or pressurized); c) underground deposit; d) tall structures (flares, distillation towers, chemins, etc …); e) basins and other process equipment; f) hazardous storage (storage of other hazardous raw materials in warehouses).

Hazards: g) earthquakes; h) floods; i) storms; j) fire; k) obsolescence.

To determine the multi-risk interactions a table is compiled, that contains the six categories of industrial items in the columns and the five categories of hazards in the rows (6 × 5 matrix). Next, based on the data gathered using the previously mentioned questionnaire, the presence and specific location of each item in the plant layout are verified, while the relevance of hazards is assessed for each case under analysis.

The categories in both columns and rows are turned on or off, depending on whether they are present (or not). In consequence, a rating is assigned to each category in a simplified binary way (0 = category not present or not considered; 1 = category considered). Then, the interaction in each cell of the 6 × 5 interaction matrix is obtained by multiplying the binary ratings of the corresponding industrial item in the column and the hazard of concern in the row. Subsequently, these interactions within the cells of the "6 × 5 matrix", are totalized column by column, where these column totals are then summed across a final row to calculate the value of total *Factor A* (refer to sub-section 3.2.1). In the original works by Pilone et al. (2021, 2022), the highest value for *Factor A* was 26, due to some predetermined no-interaction cells in the interaction matrix.

3.1.2. Factor B

Factor B depending on the hazardous substances stored in the plant, is determined by the sub-factors type (*B*1) and quantity (*B*2). Firstly, *Factor B*1 assigned ratings concerning the classes of hazardous substances considered in the Seveso III Directive (2012/18/EU) which is in line with Regulation (EC) No 1272/2008.[3] Substances that directly impact human health (*B*1*HH*) are considered those classified under Section «H» ("health hazards") and Section «P» ("physical hazards"). In contrast, substances with potential environmental impacts (*B*1*Env*) were categorized separately and included those listed under Section «E» ("hazardous to the environment"). In addition, the method includes ratings for an extra category denominated "other substances" for substances not mentioned in Annex I of Directive 2012/18/EU. Summing up, from the sub-factor type of substances (*B*1), two Na-Tech dimensions must be estimated, one related to the possible harms to human health –*NI*(*HH*)–, and the other related to the possible harms to the environment –*NI*(*Env*)–.

Secondly, the ratings assigned to the sub-factor substance quantity (*B*2) are determined by ranges associated with the fulfillment of thresholds declared for any class of substances in Directive 2012/18/EU.

3.1.3. NaTech Indicator assessment

Equation (1) proposes the latest refinements in the calculation method to determine the simplified NaTech vulnerability indicator crossing values obtained for *Factor A* and *Factor B*, (Castro Rodriguez et al., 2023a, 2023b).

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

where,

NI: NaTech vulnerability indicator.

Factor A: final number obtained in a tabular way, from the 6 × 5 interaction matrix relating industrial items and hazards categories.

*Factor B*1: rating for the type of dangerous substances stored, according to Column 1 of Annex I of Directive 2012/18/EU (Part 1).

*Factor B*2: rating for the quantity of dangerous substances stored in the plant (depending on the thresholds declared for lower tier establishments (LTE) of any category of substances in Column 2 of Annex I of Directive 2012/18/EU).

m: corresponds with index values assigned to each *"j"* section of substance within Annex I of Directive 2012/18/EU (H = 1, P = 2, E = 3, and other substances = 4).

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

Summarizing, Table 1 provides the ratings proposed by the original method for *Factor B*1 and *Factor B*2. Additionally, the table also includes the highest values for *NI*(*HH*) and *NI*(*Env*) suggested by Pilone et al. (2021), and their corresponding alert thresholds, for the simplified case in which the method was originally applied, assuming the presence of only one substance per class.

3.2. Implementing the simplified NaTech vulnerability indicator in a critical infrastructure

The implementation of the NaTech vulnerability indicator is presented here, illustrated through a case study comprising a thermoelectric plant clustered in the macro-sector "power production," according to the description given by Casson Moreno et al. (2018), while concerning the Directive (EU) 2022/2557, the facility can also be classified as energetic critical infrastructure (Fig. 2).

3.2.1. Determination of Factor A for the case study plant

Table 2 presents the determination of *Factor A* contextualized to the data of the case study plant (it can be noted that the "Total *Factor A*" is close to its highest value).

3.2.2. Determination of Factor B for the case study plant

Table 3 summarizes all the information related to the type and quantity of hazardous substances detained in the plant, along with the ratings assigned for the respective factors. In this case, one substance per class is present.

The dense fuel-oil BTZ significantly exceeded the lower-tier threshold, indicating its significant danger to aquatic environments and the potential for long-term adverse effects on aquatic life. Moreover, this substance exceeds the specific thresholds for petroleum products and alternative fuels. Conversely, the quantity of automotive diesel falls below 20% of the applicable LTE and consequently takes 0.2 as the assigned rating (refer to Table 1).

3.2.3. Assessment of NI(HH) and NI(Env) for the case study plant

Given the previously obtained information for both *Factor A* and *Factor B*, here is the final determination for *NI*(*HH*) and *NI*(*Env*) for the energetic critical infrastructure; Equation (2) and Equation (3) summarize the calculation.

$$NI(HH) = FactorA \times \frac{1}{1_{P5c}} (B1_{automot\,diesel} \times B2_{automot\,diesel}) = 1 \times (23 \times 2 \times 0.2) = 9.2 \tag{2}$$

Table 1

Rating of *Factors B*1 and *B*2, and thresholds for *NI*(*HH*) and *NI*(*Env*).

Factor Type (*B*1)	Dimension	Section	Effect	Rating
B*1*HH	Human health potential damages	H	Toxic	3
		H	Carcinogenic	2.5
		P	all	2
B*1*Env	Potential environmental impacts	E	all	3
		Other substances	all	0.5
Factor Quantity (*B*2)	> Seveso lower-tier threshold LTE			1
	>20% of the threshold for LTE (Sub-threshold Seveso)			0.6
	<20% of the threshold LTE (Sub-Seveso establishment)			0.2
$NI(HH)_{max} = 26 \times (3 \times 1 + 2.5 \times 1 + 2 \times 1) = 195$		$NI(Env)_{max} = 26 \times (3 \times 1 + 0.5 \times 0.2) = 80.6$		
NI(*HH*) alert threshold = 27		*NI*(*Env*) = alert threshold = 11		

Source: (Pilone et al., 2021).

[3] Regulation (EC) No 1272/2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006.

Fig. 2. Satellite view of the energetic critical infrastructure used as case study.
Source: Castro Rodriguez et al. (2025a).

Table 2
Interactions between vulnerable items and hazards (*Factor A*).

Factor A Interaction Matrix	Inside (I) Outside (O)	(O)	(O)	–	(O)	(O)	(O)
	→Items	a	b	c	d	e	f
↓	**Ratings**	1	1	0	1	1	1
Multi-Hazard							
(g) Earthquake	1	1	1	0	1	1	1
(h) Flood	1	1	1	—	—	1	1
(i) Storm	1	1	1	—	1	1	1
(j) Fire	1	—	1	0	1	1	1
(k) Obsolescence	1	1	1	0	1	1	1
Total ratings		4	5	0	4	5	5
Total *Factor A* = 23							

$$NI(Env) = FactorA \times \frac{\mathbf{1}}{1_{E1}} \left(B1_{fuel-oil\ BTZ} \times B2_{fuel-oil\ BTZ}\right) = 1 \times (23 \times 3 \times 1) = 69 \tag{3}$$

Based on the proposed highest values and the corresponding alarm thresholds, it is clear from the results of Equation (2) that the *NI*(*HH*) does not affect the NaTech potential, since the value found is only 4.7% of the $NI(HH)_{max}$ and is below the alarm threshold (9.2 < 27). In contrast, the value obtained for *NI*(*Env*) in Equation (3) represents approximately 85% of $NI(Env)_{max}$ and abundantly exceeds the alarm threshold (69 > 11).

In summary, the results of this initial attempt to assess multi-risk NaTech vulnerability in an energy infrastructure using the simplified indicator outlines that the presence of dense fuel-oil BTZ in high quantities, coupled with the vulnerability of industrial items to the assessed set of hazards, has raised concerns about the plant susceptibility to suffering NaTech scenarios. These scenarios could pose significant risks to both the environment and the population due to the substance hazard classification and the severity of potential top events.

While it is evident that the current method provides easy pre-screening that supports decision-making on potential NaTech, it is important to note its limitations. The highest values and corresponding alert thresholds used here are only valid under the initial assumptions of this simplified methodology—specifically when only one substance per class is considered. According to Equation (1), these maximum values are only achievable when the facility under analysis stores only one substance per defined class, and each of these substances receives the highest rating.

If multiple substances of the same class are stored, these limits no longer apply, and setting an upper limit for *NI(HH)* and *NI(Env)* becomes challenging without dividing by the total number of substances in that class. However, even this approach is problematic, as the outcome

Table 3
Ratings for *Factor B* according to the type (*B*1) and quantity (*B*2) of the hazardous substance.

Hazardous substance	Section (sub-section)	Hazard statements	LTE threshold	Quantity	B1*HH*	B1*Env*	B2
Dense fuel-oil BTZ	Environmental Hazards (E1)	H411, H226 H350, H315	100 (ton)	20000 (ton)	–	3	1
Automotive diesel	Physical Hazards (P5c)	H226, H315 H351, H411	5000 (ton)	100 (ton)	2	–	0.2

will always depend on the number of substances present and some critical information can be smoothed in the process of division. Furthermore, the wide range in the assigned ratings introduces a high degree of flexibility for the interpretation of the calculated indices *NI (HH)* and *NI(Env)*. Therefore, a robust deterministic criterion needs to be further developed.

4. Improving the NaTech vulnerability indicator: Critical discussion

Given the current limitations previously discussed, opportunities to refine the simplified multi-risk NaTech vulnerability indicator are here critically discussed to enhance the method consistency and future applicability for a broader range of stakeholders. This section addresses opportunities to improve *Factor A*, and *Factor B* and the final assessment of the multi-risk NaTech potential.

4.1. Opportunities to improve Factor A

For the sake of clarity, this sub-section has been addressed into five components that individually addressed the opportunities to improve *Factor A*, they are: 1) identification of the hazards, 2) characterization for the considered multi-hazards, 3) vulnerable industrial items, 4) dynamic vulnerability among the considered industrial items, and 5) multi-risk interaction rating between industrial items and hazards.

4.1.1. Identification of hazards

The simplified method proposed by Pilone et al. (2021) considered five fixed categories of hazards to determine *Factor A*. They correspond with four natural hazards (earthquakes, floods, storms, and fire) and one technological hazard (obsolescence).

In terms of natural hazards, the currently used categories (g) earthquakes, (h) floods, (i) storms, and (j) fire align with the main NaTech factors clustered within four macro-categories for geophysical, hydrological, meteorological, and climatological hazards, respectively. Recent studies confirm that those categories are responsible for 60% of NaTech reported in the process industry (Gao et al., 2023; Ricci et al., 2021). However, other significant factors—such as landslides, wave action, ground movement, tsunamis, tropical storms, extreme temperatures, lightning, intense winds, and heavy rains—are embedded within the current rigid hazard classification, potentially limiting recognition of their impacts on industrial infrastructure. Indeed, there exists evidence that industrial infrastructure experiments with different extents of susceptibility (Castro Rodriguez et al., 2024; Ricci et al., 2023a, 2023b), when exposed independently to natural factors currently clustered in the category “storms”.

In summary, it would be advisable to have more flexibility in the selection of the hazards taking into account their influence across the zones of interest. Table 4 offers the classifications for 15 natural factors divided into macro-categories according to the criteria of various authors (Gill and Malamud, 2014; Ricci et al., 2021).

Additionally, the input for multi-hazards could be not only limited to the natural hazard but also allow the introduction of other categories of interest, such as aging phenomena, or neighboring plant hazards, all of them from the technological dimension. However, to include additional hazards different from natural factors, further research is required to identify spatial indicators and the potential cascading effects between the new factors considered.

4.1.2. Characterization of multi-hazards

During the determination of *Factor A*, all the categories for the multi-hazard input were considered (refer to sub-section 3.2.1). As a result, rate 1 was assigned to each hazard category without considering differences in their incidences. However, as early discussed, the current rating system fails to characterize: i) the differences in the spatial influence of each natural hazard on the industrial context under consideration, ii) the specific vulnerability of the kind of industrial asset given natural hazards, iii) the potential interactions among natural hazards causing cascading effects.

Table 4
Natural hazards: macro-categories and codes.

Macro-categories	Geophysical	Meteorological	Hydrological	Climatological
Hazards (Code)	- Earthquake (EQ) - Tsunami (TS) - Volcanic activity (Va) - Landslide (LA) - Shallow processes (SP)	- Storm (St) - Extreme temperature hot (Eth) - Extreme temperature cold (ETc) - Tropical storm (TSt) - Lightning (LN) - Fog (FG)	- Flooding (FL) - Drought (DR) - Wave action (WA)	- Wildfire (WF)

The following subsections will discuss the elements listed above to highlight the necessity to operationalize a “location priority factor” that accounts for the spatial influence of each hazard, the conditional probability of NaTech events based on the industrial macro-sector analyzed, and the cascading effects between natural hazards by assigning interaction-based ratings. Additionally, the influence of cascading interactions among neighboring infrastructures within the same industrial context should be considered and characterized as an additional hazard factor.

i Differences in the spatial influence of natural hazards

Estimating the likelihood of devastating consequences from a natural disaster is one of the most challenging aspects of NaTech risk assessment (Reniers et al., 2018). This complexity is further amplified when attempting to harmonize the impacts of different disasters in the same area using a common multi-risk metric.

As mentioned before, one possible approach is to represent independent hazards threatening a common area using spatial indicators. For this purpose, previous results that spatially characterize vulnerability within the context of the same industrial case study (Castro Rodriguez et al., 2023b), can be used to illustrate differences in the spatial influence of hazards (Fig. 3). There, the territorial vulnerability to various hazard factors is represented using normalized values [0, 1]. Further, details about the inputs of these methods and how to determine the spatialized indicators can be found in Beltramino et al. (2022).

It must be considered that the industrial context includes not only the on-site area inside the fence of the plant but also the surrounding territory (off-site), comprising approximately 280 ha composed of 70 homogeneous cells mutually exclusively. Fig. 3a) shows the industrial context’s vulnerability to earthquakes. While this vulnerability should not be completely ignored, only a few cells with low vulnerability appeared at the top right of the grid. These findings align with the seismic zone danger levels in Italy (Dipartimento della Protezione Civile, 2023) considering the plant location.

Focusing on Fig. 3b), it is not difficult to note how almost all the cells included in a radius of 200 m around the perimeter of the plant (violet dark line, representing the exclusion area), are critically vulnerable to the impact of floods. The rest of the visual field oscillates between critical and high vulnerability, and just a few cells with low vulnerability are at the top right of the grid. The potential impact of this natural hazard is determined by the plant location proximity to the riverbed, which flows on both sides. The territorial vulnerability for floods based on the plant location is consistent with the maps of danger for flood risk in Italy (Autorità bacino, 2020, 2022). In addition, this type of natural hazard can damage industrial items in several ways, including by buckling, breaking pipes and connections, overfilling process

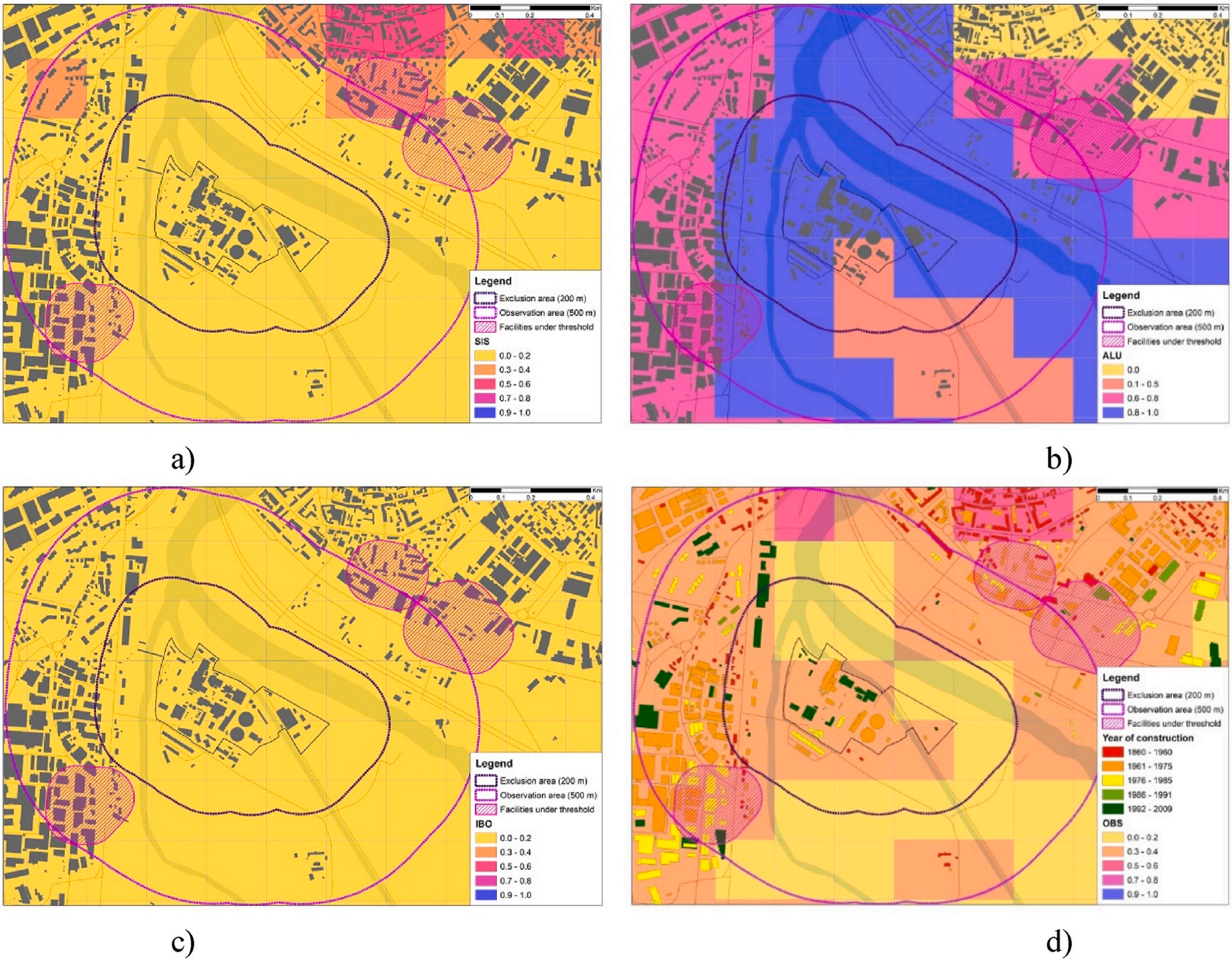

Fig. 3. Individual influence of four hazard categories within the industrial context under study, together with the representation of damage areas for technological scenarios (internal and external lines around the plant): a) earthquakes, b) floods, c) wildfires, and d) obsolescence. Source: Castro Rodriguez et al. (2023b).

equipment, moving and flipping structures, and pushing things to the equipment, which can cause puncturing (Necci and Krausmann, 2022). Conversely, Fig. 3c shows how the natural factors of wildfires, given the location, may be disregarded in this case.

It is important to note that one of the pros of the simplified NaTech vulnerability indicator is the inclusion of obsolescence among the multi-hazard categories analyzed. Then, in Fig. 3d), obsolescence is depicted as a linear and generalized trend, based on the construction age of buildings, gradually impacting the industrial context as outlined in Beltramino et al. (2022). This territorial indicator was considered important for industrial infrastructures, given that 50% of process plants in Europe operate past their intended lifespan (Vairo et al., 2018). It is noteworthy that certain facilities within the plant perimeter, such as the orange structures including storage tanks, were constructed between 50 and 65 years ago according to the scale, suggesting that obsolescent phenomena may be present. In the process industry field, obsolescence is defined as the process of equipment, standards, and regulations changing over time (Milazzo and Bragatto, 2019). However, it is critical to distinguish between obsolescence and aging phenomena, since the latter is not always linked to the amount of time the component has been in operation and may be accelerated by the incidence of natural factors (Vitale et al., 2024). Therefore, while pressures like obsolescence can impact the system and alter its normal performance (Intergovernmental Panel on Climate Change, 2023), their gradual nature and interactions with instantaneous factors like natural hazards require further research.

In summary, the differences in the four hazards discussed outline significant variations in the influence of various independent hazards on the industrial context under analysis, according to the extension of each phenomenon. An opportunity to address this point consists in the introduction of varying degrees of influence according to the contextualization of each hazard extension through a "location priority factor".

ii Specific vulnerability of industrial infrastructure to natural hazards

In addition to assessing the magnitude and territorial distribution of each natural hazard within the industrial context, it is crucial to evaluate its potential to trigger NaTech events relevant to the specific industry being analyzed. For example, Fig. 4 shows the relative frequency (or belief) of lightning-triggered NaTech events across different macro-sectors within the process industry, as derived from historical data. Additional information on the data retrieval and calculations can be found in Castro Rodriguez et al. (2024), while the raw data is available in Castro Rodriguez et al. (2023c).

The energetic critical infrastructure used as a case study falls within the power production macro-sector, with a belief of approximately 0.06. Consequently, if data is available, the conditional probability of each

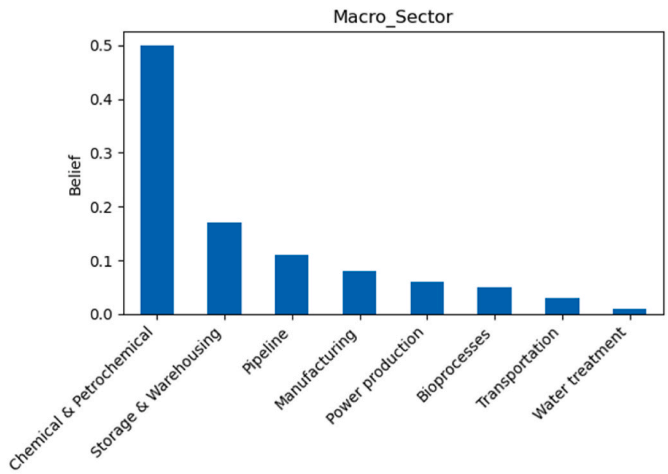

Fig. 4. Relative frequency (belief) for the different industrial macro-sectors affected by lightning strikes. Source: modified from Castro Rodriguez et al. (2024).

hazard triggering NaTech events—based on the industrial macro-sector under analysis—should be incorporated into the "location priority factor" introduced in the previous subsection.

Additional data on the impact of specific natural hazards—such as floods, earthquakes, lightning, and extreme temperatures—on the industrial sector can be found in the literature (Cozzani et al., 2010; Gao et al., 2023; Krausmann et al., 2011; Renni et al., 2010; Ricci et al., 2023a, 2023b). However, significant efforts are still needed to generate quantitative data on NaTech events triggered by less-studied natural hazards.

iii Cascading effect caused by interactions among natural hazards

The current simplified NaTech vulnerability indicator method does not include the possible cascading effects among the multi-hazard categories. This means that the possible interactions between the different dangerous events are not taken into account. When studying multiple hazards, cascading effects have to be considered because a chain of linked disruptive events may have worse results (escalation) than the sum of the effects of a single hazard (Zeng et al., 2023). Specifically, when a natural factor propitiates one or more different natural hazards (also known as disaster chains), these interactions can be understood as a change in the conditional probability of a secondary hazard given a primary hazard (Gill and Malamud, 2014).

Previous research reports possible interactions among natural hazards using a 21 × 21 interaction matrix. From this, 90 possible interactions were identified (see Fig. 5) by examining more than 200 references from the scientific literature (Gill and Malamud, 2014, 2017). In these studies, diverse mechanisms of interaction have been identified. First, a natural factor triggers one or more secondary natural hazards: for example, lightning igniting wildfire. Second, a natural hazard increases the probability of secondary hazards (i.e., wildfires increase the probability of a landslide). Third, the natural hazards overlap in space and time.

Evidence about the NaTech events that occurred in China indicates that around 30% of them were generated by multiple interactions of natural factors, while just 2.4% registered more than two natural factors interacting (Gao et al., 2023). So, based on this frequency within the process industry, interactions between two natural factors that trigger technological factors are significant, while those that involve more than two natural factors causing a subsequent technological event could be classified as isolated events.

Given all the above, an opportunity to improve the current method consists of considering the cascading effects between pairs of natural hazards, and assigning ratings to the interaction criteria given by Gill and Malamud (2014). Understanding these linkages undoubtedly increases the stakeholder's awareness.

iv Territorial density of infrastructures and synergy with neighboring infrastructure

Since natural hazards may cause multiple NaTech events in the same location at the same time, another kind of multi-hazard interaction that may happen is the NaTech domino effect. NaTech domino effects are complicated situations involving a cross-category of hazards. They occur when natural factors cause a first industrial event that leads to more, possibly higher-order disastrous scenarios (Zeng et al., 2023). In industrial clusters, this phenomenon may also occur when a secondary technological scenario is caused by a previous NaTech event that came from a neighboring plant (Reniers and Cozzani, 2013). Thus, the density of industrial infrastructures within the same spatial location (industrial context) increases the possibility of multiple NaTech events occurring in the same time frame, as well as the NaTech domino effect, causing greater damage, and challenging the efficacy of emergency responses.

To clarify this point, Fig. 6 shows the vulnerability of the industrial context under study, plotting the major accident hazard indicator (RIR for the Italian acronym). This indicator highlights neighboring facilities within the same industrial context subject to major accident hazards, as defined by Italian Legislative Decree June 26, 2015, no.105[4] which fully transposed the Seveso III Directive. It also identifies exclusion and observation zones based on different distances applied around the plant, according to the regional guidelines (Regional Council Resolution No. 17–377, July 26, 2010).[5] Details for the determination of the RIR indicator can be found in Castro Rodriguez et al. (2022) and Beltramino et al. (2022).

Focusing on the power production plant under study, it is evident that the 500 m radius around the plant perimeter (marked by the purple line, representing the observation area) intersects with blue cells. These cells indicate the vulnerability zones of three neighboring sub-threshold Seveso facilities. Focusing on the cells within the exclusion area (200 m) around the power production plant, only a few points of contact with blue cells from other facilities were identified.

Therefore, an opportunity to enhance the current method for determining NaTech vulnerability is to consider neighboring infrastructures within the same industrial context as an additional hazard factor. To assess the extent of interactions among neighboring infrastructures, the spatial method for multi-scale characterization of industrial infrastructure vulnerability to multiple hazards, as described by Castro Rodriguez et al. (2025a), would be extremely valuable.

4.1.3. *Vulnerable industrial items*

The Pilone et al. (2021) method effectively accounts for diverse categories of industrial items exposed to multiple hazards. However, focusing solely on these categories may lead to the oversight of other key components. Table 5 compares the current items in columns with other categories in rows.

The rows cover all categories used by several authors throughout different works on Na-Tech field. (Castro Rodriguez et al., 2024; Cozzani et al., 2010; Krausmann et al., 2011; Necci and Krausmann, 2022; Renni et al., 2010; Ricci et al., 2023a, 2023b). The interactions between

[4] Legislative Decree No. 105 of June 26, 2015, "Implementation of Directive 2012/18/EU on the control of major-accident hazards involving dangerous substances." Italian Official Gazette General Series No. 161 14/07/2015-Suppl. Ordinary No. 38.

[5] Regional Council Resolution No. 17–377, July 26, 2010, "Approval of Guidelines for Industrial Risk Assessment in Spatial Planning–Strategic Environmental Assessment Procedure and Technical Elaboration on Major Accident Hazard." Official Bulletin of the Piedmont Region No. 31, 05/08/2010.

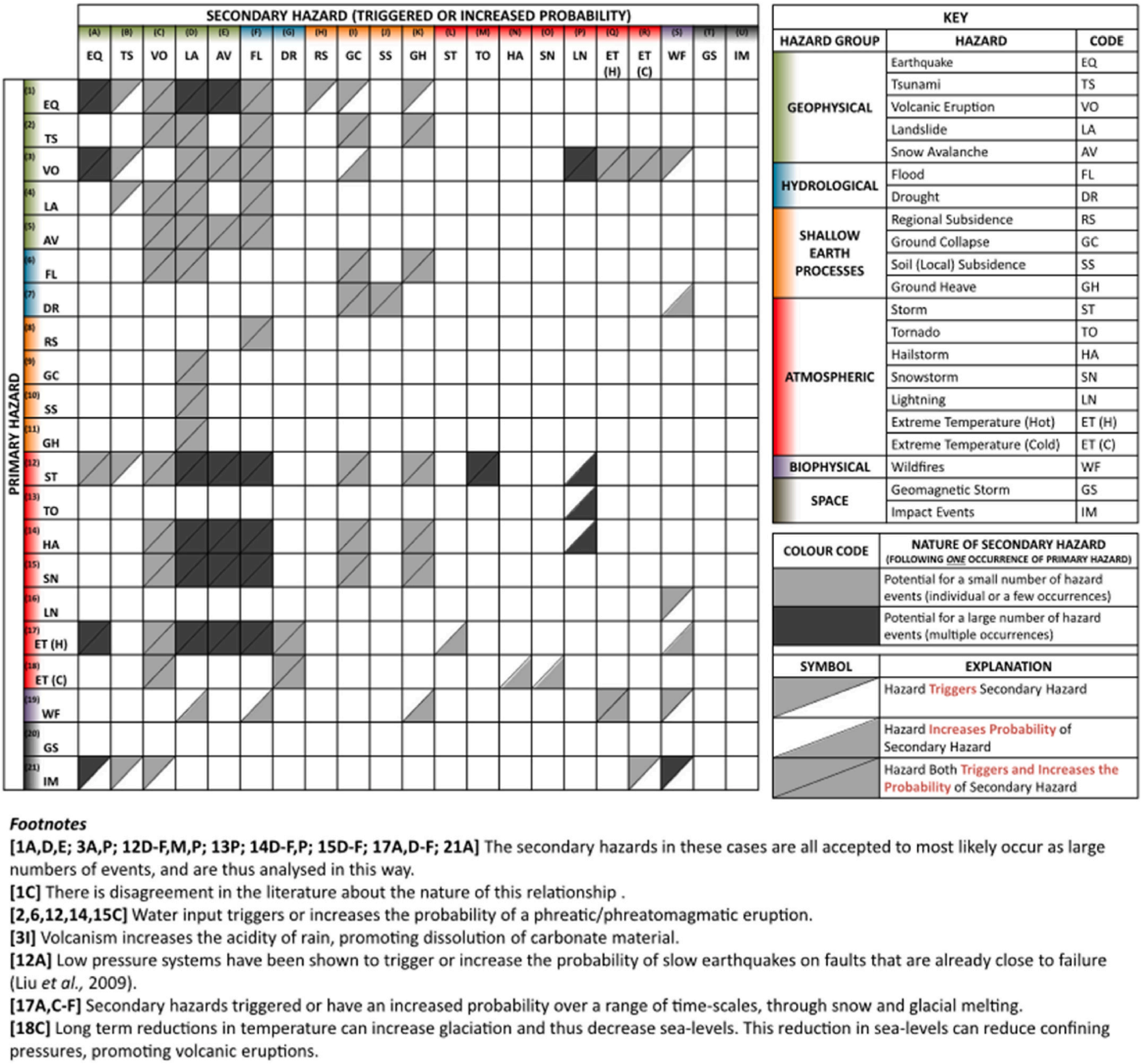

Fig. 5. Identification of hazard interactions. Source: Gill and Malamud (2014).

columns and rows assess the conceptual consistency of the compared categories, using an ordinal scale established by Zuccaro et al. (2018). This scale defines relationships as L (low/weak), M (medium/strong), or H (high/very close). The cell was shaded when there was no correspondence between categories.

Table 5 illustrates how the perspectives of various authors and the types of natural factors under investigation affect the categorization of vulnerable equipment. Most columns show at least a medium level of compatibility, indicating that the interacting categories, while not identical, have significant conceptual overlap. This highlights the consistency of the existing categories when compared to similar research.

Only a few of the 19 row categories showed high conceptual overlap with the current method item categories, such as (1; b), (7; e), and (18; f). Conversely, some row entries had only marginal alignment with the current categories, highlighting gaps in the existing definitions. For instance, categories like “electrical and electronic equipment” (3), “compressors and pumps” (4), “pipelines and pipework” (5), “tanker” (6), “valves and instrumentation” (8), and “waste disposal” (19) are not explicitly defined and are often assumed to fall under more general categories; however, this assumption may introduce uncertainty.

Regarding the previously mentioned categories that the current method weakly considers, categories 4 and 5 accounted for 21% of NaTech events triggered by floods (Cozzani et al., 2010), category 3 independently recorded 26% of NaTech events caused by lightning (Castro Rodriguez et al., 2024), groups 6 and 8 accumulated around 28% of NaTech events triggered by cold waves (Ricci et al., 2023b), and group 19 accounted for 25% of events triggered by heat waves (Ricci et al., 2023a).

Table 6 proposes a comprehensive harmonization of industrial item categories, ensuring consistency with both previous and current research in the NaTech field while enhancing compatibility with historical event data. These categories can be selected based on the specific

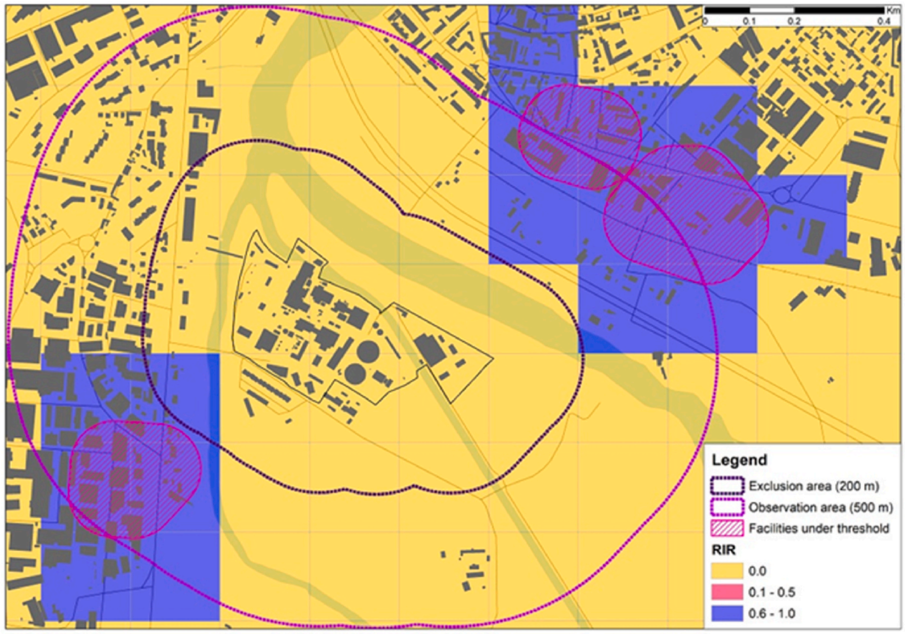

Fig. 6. Vulnerability representation of major risk hazards induced by neighboring facilities in the same industrial context. Source: Castro Rodriguez et al. (2025a).

Table 5
Cross-check between the current industrial items considered and other categories found in specific NaTech-triggered historical analysis.

	Items	**a)**	**b)**	**c)**	**d)**	**e)**	**f)**
No	Description	Basins for water treatment	Storage tanks	Underground deposit	Tall structures	Basins and other process equipment	Hazardous storage
1	Storage equip		H	M			L
2	Flare stacks				M		
3	Electrical & Electronic equip					L	
4	Compressors and Pumps					L	
5	Pipelines and Pipework					L	
6	Road/rail tanker		L				
7	Process equip.	L			M	H	
8	Valves and instrumentation					L	
9	Cylindrical vessels		M				
10	Atmospheric storage tank		M	L			
11	Pressurized vessels		M				
12	Heat exchanger					M	
13	Phase separators	L				M	
14	Column				M	M	
15	Stack				M		
16	Dike/Pond	M				L	
17	Sewers	M				L	
18	Warehouse						H
19	Waste disposal	M					

Legend: L (low/weak relationship), M (medium/strong relationship), H (high/very close relationship), shaded cells (not applicable).

items present in each facility under consideration, which represent indeed an opportunity for improvement for the simplified method.

4.1.4. Dynamic vulnerability among the considered industrial items

The impact of a hazard on internal industrial infrastructure can increase the specific vulnerability to a second hazard, thereby potentially amplifying the effects of a secondary event through on-site domino effects. This concept is defined as dynamic vulnerability, where “the sequence of cascading events causes a progressive increase in the vulnerability of the element exposed, depending on the evolution of the

Table 6
Proposal of harmonized categories of equipment, codes, and description.

Equipment Categories	Code	Description
Storage equipment	SE	Atmospheric and pressurized tanks.
Underground storage equipment	USE	All the underground items that can be present in the plant.
Flare stakes	FS	Tall structures that are present in the plant.
Process equipment	PE	Including vessels, heat exchangers, separators, condensers, reactors, equipment, and accessories inherent to the principal unitary operations of the plant.
Pipework	PW	Including pipe systems and valves.
Road/rail tanker	TK	Road tanker and rail tanker (Transportation of hazardous materials).
Machinery	MC	Including compressors and pumps.
Electrical equipment and electronic devices	EE	Including sensors, instrumentation, energized lines, and networks belonging to the plant.
Other hazardous storage	HS	Warehouses, cylinders, big bags, waste disposal.
Basins and water treatment elements	BWT	Including dikes, ponds, sewers, and basins (even if not just for water treatment).
Auxiliary systems and their utilities	ASU	Conceived for those auxiliary systems and utilities including the emergency response to the abnormal operation.

damaging process" (Zuccaro et al., 2018). Therefore, the dynamic vulnerability consideration constitutes an opportunity to improve the current methodology, identifying the dynamic vulnerability of critical items and equipment within the industrial asset. In this regard, the proximity in the layout, and the functional interconnections between pairs of industrial items, are crucial in the analysis. The analysis of internal scenarios and simulations offers robust criteria for this assessment.

4.1.5. Multi-risk interaction rating

Under the current rating method, all item categories receive the maximum possible values, meaning that *Factor A* will always reach its extreme value for the analyzed conditions. While this may be useful for a worst-case scenario prescreening from the perspective of local planners, it undermines the objectivity of a case-by-case assessment. This approach fails to account for the unique realities of each location, which is essential for operators and competent authorities within public administration, who are responsible for controlling major industrial accidents.

As an example, Fig. 7 illustrates the relative frequency (belief) of various types of industrial equipment involved in lightning-triggered NaTech events within the process industry, based on historical data.

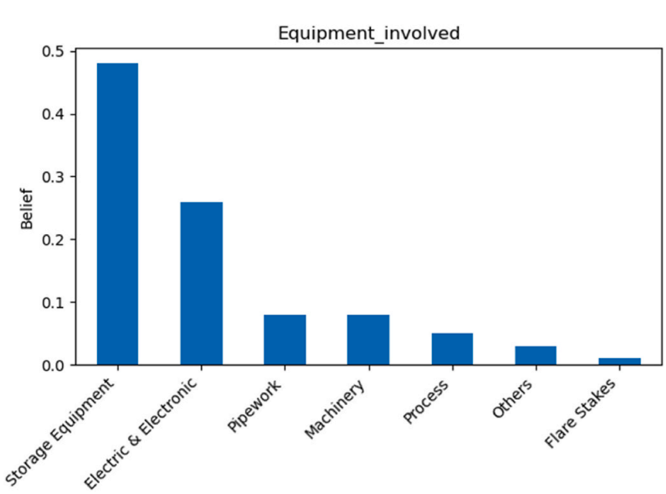

Fig. 7. Relative frequency (belief) for the different industrial equipment categories affected by lightning strikes after treating the data uncertainty.

The analysis reveals differences in sensitivity among industrial items to the natural hazard in question (lightning). Additional details on how this data was determined can be found in Castro Rodriguez (2024). Similar data is available for natural factors such as floods and extreme temperatures (hot and cold waves) (Cozzani et al., 2010; Ricci et al., 2023a, 2023b). In contrast, further research should be conducted to obtain consistent data for other hazards.

To enhance multi-risk assessment across harmonized item categories and the hazards they face, a valuable improvement would be the incorporation of quantitative criteria derived from historical analyses of NaTech-triggered events.

4.2. Opportunities to improve Factor B

Recapping, *Factor B* encompasses the hazards factor that arises from scenarios where the containment of dangerous substances is compromised. Some authors suggest using probabilistic methods to guess how much of the hazardous substance inventory will be released due to natural disasters (Necci and Krausmann, 2022; Suarez-Paba and Cruz, 2022).

However, predicting the release of hazardous substances due to natural disasters is challenging given the complex nature of these events, and because of the incomplete information. When looking at the available data for classifying dangerous substances used by Seveso establishments, this classification and quantification are kept under Annex I of the Seveso III Directive, considering the potential consequences for human health, the environment, and physic-built infrastructure.

The European Commission classified the industrial establishments as lower-tier (LTE) or upper-tier (UTE) based on their maximum storage capacity of dangerous substances, and requires notifications for major accidents when at least 5% of the inventory respect the UTE threshold is involved. Regarding this issue, plants outside Seveso III may still meet these criteria, even if they are not under the safety requirements outlined by the 2012/18/EU Directive. While the rating-based system developed by Pilone et al. (2021) provides a useful idea for evaluating substance criteria in both Seveso and non-Seveso facilities, certain gaps and inconsistencies with the European legislation were identified in the classification of substance types and the rating assignment to the quantities stored (see subsections 4.2.1 and 4.2.2). Subsection 4.2.3 address this gaps proposing a complementary index designed to evaluate the potential for major industrial accidents based on hazardous substance criteria.

4.2.1. Limitations in the classification of the type of substance

First, it is important to recall that the current method requires labeling the substances stored in the plant, making specific mention of sections «H», «P», and «E» listed in Part 1 of Annex I of Directive 2012/18/EU and "other substances" not included in this Annex I. However, the eventual presence of substances classified in Section «O» "Other Hazards" is omitted. This could be adjusted by simply including Section «O» in one of the current dimensions proposed for *Factor* $B1$. For instance, $B1$ (*Env*) may consider the sections «E», «O» and "other substances", while $B1$(*HH*) keeps the sections «H» and «P».

Conversely, the current dimensions for $B1$ do not explicitly consider substances that could be harmful simultaneously to both people and the environment. For example, gasoline is classified as a flammable liquid (P5a) and, at the same time, as hazardous to the aquatic environment (E2). Furthermore, although the current dimensions of $B1$ account for the consequences to human health and the environment, they do not specifically address potential damage to physical infrastructure, as this is implicitly covered under $B1$(*HH*).

4.2.2. Shortcomings in rating the quantity of substances stored

Since the current ratings fall within the range [0, 1], they do not adequately emphasize the total value of *Factor B*. Mathematically, *Factor B* is defined as $B = B1 \times B2$, which means that the value of *Factor B* decreases when $B2$ is in the range [0, 1) or, at best, maintains the value of $B1$ when $B2$ equals 1.

In addition, these current ratings are not sensitive to differences in substance volume within the same subcategory of type of substances. For instance, the same value of 1 is assigned to two hypothetical substances X and Y that surpass the lower-tier threshold, regardless of how much the amount may be higher than the limit.

4.2.3. Major accidents potential based on hazardous substances criteria

On the one hand, regarding the substances classification issues, notes 4, 5, and 6 of Annex I of the 2012/18/EU Directive provide unambiguous rules that can be applied to address the shortcomings in rating the type of hazardous within a facility. In brief, the hazardous substances (including wastes), potentially located in an establishment, shall be provisionally assimilated into the most similar dangerous category or substance listed in Annex I 2012/18/EU. Additionally, when a substance fits into more than one classification, the lowest acceptable levels (critical) must be used for each group of categories that match the relevant classifications. This includes substances listed in Part 2 of Annex I of Directive 2012/18/EU.

Moving to the gaps detected in the rating assignment for the quantity of hazardous substances stored in the plant, it is proposed to replace the $B2$ ratings with the compliance index. This index calculates the ratio between the quantity of hazardous substances stored and the corresponding threshold for each specific substance, as outlined in note 4 of Annex I of the 2012/18/EU Directive. This approach would account for both the presence of multiple substances and the most abundant in each class.

From the previous two considerations, an innovative index (enhanced *Factor B*) to evaluate the potential for major industrial accidents based on hazardous substance criteria was re-designed in total alignment with the legal requirements of the 2012/18/EU Directive. Nonetheless, it extends its scope to include not only major establishments but also the so-called non-Seveso facilities. Further details about this innovative index are provided in Castro Rodriguez (2024) and Castro Rodriguez et al. (2025b).

4.3. Opportunities to improve the final assessment of the multi-risk NaTech potential

Referring to the discussion in subsection 3.2.3 on interpreting the NaTech indicator, it is important to note that relying solely on a single-point value may obscure whether case specific vulnerabilities stem primarily from the susceptibility of industrial infrastructure to multiple territorial hazards (*Factor A*) or are mainly influenced by the volume and classification of hazardous substances present (*Factor B*).

While a single-point index with predefined thresholds is widely accepted for its ease of interpretation—particularly for simplified early warning at a primary decision-making level—the multidimensional nature of NaTech events requires a more comprehensive evaluation. Given the opportunities previously discussed to refine both *Factor A* and *Factor B*, it is now crucial to consider how the final multi-risk assessment can be improved.

Enhancing *Factor A* should not only provide a single global value reflecting multi-risk interactions between industrial infrastructure and hazards at a given location but also offer intermedium strategic advantages by introducing more sensitive rankings for contextualized industrial items and hazards, in columns and rows respectively, including cascading effects. Meanwhile, improving *Factor B* allows for a more detailed individual assessment of potential major industrial accidents based on hazardous substance criteria.

To integrate these refinements, a decision matrix combining the independent evaluations of both enhanced factors—represented as (A; B) cells—should be introduced. This approach would facilitate risk assessment through a categorical decision scale with varying levels of risk tolerance, aligning with established criteria for decision matrices in Na-Tech research (Krausmann et al., 2011; Suarez-Paba and Cruz, 2022).

In this framework, system preparedness will depend on risk acceptability, guiding the implementation of minor or major intervention strategies. Depending on the localization of the (A; B) cells, these strategies may focus on retrofitting infrastructure to mitigate the impact of critical hazards and/or reinforcing safety barriers related to substance storage, including measures for improved inventory management.

5. Conclusions and implications

Recap: The concept of multi-risk is crucial for enhancing the NaTech risk assessment. In this regard, Pilone et al. (2021) created a simplified indicator for local planners to prescreen the NaTech vulnerability of plants exposed to multiple hazards which is also considered a factor in assessing the dangerousness of hazardous substances stored on-site. After its implementation in a case study from the energetic sector, the methos was critically discussed focusing on opportunities to improve its initial step stressing further elaborations and established criteria.

Regarding multi-hazards: A wide flexible selection of natural hazards was proposed based on the classification of 15 factors divided into four macro-categories (geophysical, meteorological, hydrological, and climatological). To better characterize the hazards of concern, it arises the necessity to develop a “location priority factor” that considers the following criteria: i) differences extent of the hazards spatial influence according to their contextualized extensions, ii) the conditional probability of each hazard to triggered NaTech given the industrial macro-sector under analysis (if data is available), iii) the cascading effects between pairs of natural hazards assigning ratings based on their interactions.

Multi-hazard inputs should not be limited to natural hazards alone. However, incorporating additional factors such as aging phenomena or hazards from neighboring plants requires further research to identify spatial indicators and potential cascading effects.

Concerning multi-vulnerable elements: Eleven categories of industrial items were proposed ensuring not only consistency with NaTech research and historical event data useful to support the assessment but also providing flexibility to choose the infrastructural items of interest. For further analysis of the dynamic vulnerability of the industrial items, it is important to consider the proximity and functional interconnections between each pair of vulnerable items.

Multi-risk assessment between infrastructure and hazards: A valuable improvement is the incorporation of quantitative criteria derived from historical NaTech-triggered analyses to assign the interactions between industrial items and hazards in their surroundings.

Hazardous substance factor: An innovative index to evaluate the potential for major industrial accidents based on hazardous substance criteria was re-designed to align with the criteria in the current European legislation.

Final assessment of NaTech potential: A decision matrix combining the independent evaluations of enhanced *Factor A* (infrastructure vs. hazards) and *Factor B* (hazardous substances), supports risk assessment through different levels of tolerance guiding the preparedness of the system.

Implications: This research identifies opportunities to improve the multi-risk NaTech vulnerability assessment of industrial infrastructures, advancing the anticipation of technological scenarios triggered by natural hazards. These enhancements contribute to strengthening resilience and adaptive capacity in line with international strategies.

The conceptual ideas presented remain open to further refinement, while future research is needed to translate them into practical methodologies and case study applications. Validation should be pursued by aligning results from ongoing implementations with documented past accidents.

CRediT authorship contribution statement

David Javier Castro Rodriguez: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Antonello A. Barresi:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Micaela Demichela:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Ethics statement

This research did not involve any applicable ethics statement, and all research procedures were carried out following the requirements for ethical principles.

Funding

This study was carried out within the RETURN Extended Partnership and received funding from the European Union NextGenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 August 2, 2022, PE0000005).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The author Micaela Demichela serve as part of the Editorial Board Members of the journal. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors recognize the help of Ph.D. Gabriele Baldissone for his precious advice. Furthermore, we sincerely appreciate the reviewers' constructive feedback, which has significantly strengthened the manuscript.

Data availability

This article utilizes data previously published in earlier works, which can be accessed through the list of references.

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