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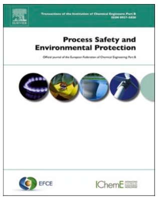

“Critical infrastructure multi-risk deployment: an innovative framework to support NaTech preparedness in industrial facilities”

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ABSTRACT

NaTech events—technological accidents triggered by natural hazards—may lead to catastrophic scenarios harming people, the environment, and the economy. Yet, given the multi-risk nature of NaTech scenarios, many industrial facilities remain unprepared due to the lack of context-specific guidelines. This research develops a multi-risk framework based on previously discussed opportunities to strengthen a NaTech indicator, translating it into an operational methodology to improve industrial preparedness for NaTech events. Consequently, the Quality Function Deployment tool was adapted into the Industrial Critical Infrastructure Multi-Risk Deployment (ICI-MRD) framework—a practical roadmap for integrating advanced multi-risk considerations into industrial safety design. This novel adaptation addresses criteria from disaster risk reduction, land use planning, policy analysis, and resilience engineering by combining innovative engineering tools with multidisciplinary approaches. Moreover, a location priority factor (LPF) was introduced to contextualize the territorial vulnerabilities. A rating system was integrated for multi-risk assessment, including criteria based on quantitative historical data and qualitative evaluation when deterministic data is unavailable. Five categories of priority were associated with the punctual infrastructure multi-risk value as a warning metric. The ICI-MRD framework was then tested in an energy-critical infrastructure, considering four natural hazards, their cascading interactions, and assessing their impact on eight categories of industrial items that mutually interact. The final ICI-MRD output value of 2.07, corresponding to a “moderate” priority, provides data-driven guidance for updating emergency protocols through the analysis of intermediate outputs. These outputs help decision-makers to provide vulnerability-centered strategies to improve both industrial and territorial preparedness while fostering dialogue among operators, practitioners, governments, and the public.

Abbreviations: AHP, Analytical Hierarchy Process; ASU, Auxiliary systems and their utilities; BWT, Basins and water treatment elements; CCF, Coping capacity factor; CI, Critical infrastructures; DR, Drought; EE, Electrical equipment and electronic devices; EQ, Earthquakes; ETc, Extreme temperature cold; ETh, Extreme temperature hot; EU, European Union; FG, Fog; FL, Flooding; FMEA, Failure mode and effect analysis; FS, Flare stakes; HAW_k, Absolute weight of each hazard category “k” across the multi-vulnerability of the equipment categories; HoQ, House of Quality; HRW_k, Hazard relative weight of each hazard category “k”; HS, Other hazardous storage; ICIs, Industrial critical infrastructures; IAW_e, Absolute weight of each item category “e”; ICI-MRD, Industrial Critical Infrastructure Multi-Risk Deployment; Inf_k, Influence of each Haz_k to the industrial context under consideration; $IntW_k$, Interaction weight factor for each Haz_k concerning the total $k_{i;j}$ interactions; $IRHazk_{i;j}$, Hazard interaction rank to each cell $k_{i;j}$ within the interaction hazard matrix; IRW_e, Relative weight of each item category “e”; $IRW_{e\ max}$, LPF_k value assuming $P(NaTech_{MS}|Haz_k) = 1$; $k_{i;j}$, Every single cell within the interaction hazard matrix where the hazard “k_i” interacts with the hazard “k_j”; LN, Lightning; LPF, Location priority factor; LFP_{k*}, location priority factor simplified for each Haz_k assuming $P(NaTech_{MS}|Haz_k = 1)$; $LPF_{k\ max}$, Maximum value for the location LPF the hazard “k”; MC, Machinery; MCDM, Multi-Criteria Decision Making; $MRI_{k;e}$, Multi-risk interaction between each single hazard on each vulnerable item; MS, Industrial macro-sector; NaTech, Technological scenarios involving the release of hazardous materials caused by a natural hazard; Ng, Lightning density to the ground; PE, Process equipment; PGA, Peak Ground Acceleration; *PIMRV*, Punctual infrastructure multi-risk value; $PNaTech_{MS}|Haz_k$, Conditional probability of NaTech occurrence in the industrial macro-sector (MS) under analysis, triggered by the hazard Haz_k; PW, Pipework; QFD, Quality Function Deployment; QFDE, QFD for the environment; SE, Storage equipment; SP, Shallow processes; St, Storm; TK, Road/rail tanker; TS, Tsunami; TSt, Tropical storm; Tv, territorial vulnerability index; USE, Underground storage equipment; Va, Volcanic activity; LA, Landslide; WA, Wave action; WF, Wildfire.

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1. Introduction

Between 2000 and 2019, in only twenty years, there were 7348 recorded disasters caused by natural hazards. These events led to the loss of 1.23 million lives, affected 4.03 billion people, and resulted in global economic losses estimated at around US$ 2.97 trillion, representing a sharp increase in the number of recorded disaster events and losses by comparison with the previous twenty years (CRED and UNDRR, 2020). Specifically, natural events can severely impact industrial infrastructure, triggering secondary technological accidents—known as NaTech events (Krausmann et al., 2017)—that may involve the release of hazardous materials, leading to fires, explosions, or large-scale toxic spills (Misuri et al., 2023). These scenarios can result in catastrophic health consequences, environmental pollution, and significant economic losses.

NaTech events may occur wherever hazardous industrial facilities are located in areas exposed to natural hazards (Krausmann et al., 2019). The potentially disastrous consequences of these events—combined with the increasing intensity and frequency of natural hazards due to climate change along with the growth of industrialization (Yalçın and Gürün, 2025)—have intensified the global demand for effective NaTech risk assessment and management (Dehghanisanij et al., 2024). In addition, NaTech events are prone to causing domino effects, in which equipment initially impacted by natural hazards triggers further on-site or off-site escalation, potentially leading to large-scale disasters or affecting nearby infrastructure (Chen et al., 2020). Due to the complexity of NaTech events, which makes prevention challenging, holistic approaches focused on vulnerability assessment should be adopted to minimize losses and enhance safety (De Rademaeker et al., 2014).

The Sendai Framework for Disaster Risk Reduction (UNDRR, 2015) and its predecessor, the Hyogo Framework for Action (UNDRR, 2007), represent key milestones in the global effort to strengthen resilience against disasters driven by both natural and human-induced hazards. Over time, this discourse has undergone a significant shift—from a traditional emphasis on response and recovery to natural disasters to a more proactive attitude centered on prevention and implementation of barriers (Vu et al., 2025). However, safety barrier performance can be significantly impacted in extreme conditions, as noted by Landucci et al. (2017).

Moving to the perspective of NaTech risk governance, global regulatory authorities have generally provided limited attention to the vulnerability issue. For instance, Directive 2012/18/EU (Seveso III), which represents a benchmark for industrial plants within the European context, acknowledges the potential impact of certain natural events—such as earthquakes and floods—in triggering major accidents but does not account for other types of NaTech events. Moreover, the analysis of the transposition of Seveso III in France and Italy (two of the more industrialized European countries) reveals that the available policy tools for the high-risk industrial sites are more centered on hazard-factor inventories than on vulnerability-focused analysis (Tannous et al., 2025). To address this gap, it is essential to raise awareness of industrial vulnerability to natural hazards while strengthening preparedness for potential NaTech events. However, in the past decade, it has become evident that industrial facilities are often unprepared for NaTech events, primarily due to the absence of clear guidelines for implementing context-specific countermeasures (El Hajj et al., 2015).

In this regard, an action that contributes to raising the awareness of NaTech risks has been introduced by the EU Joint Research Center, which has published a guideline for hazardous industrial site operators and national authorities considering the multi-stakeholder nature of these phenomena (Necci and Krausmann, 2022). While these guidelines represent a significant step forward in NaTech risk management, they do not fully address its multi-hazard dimension, in which the initial triggering event may result from cascading interactions among multiple hazardous factors. For instance, some NaTech events may be associated with the interaction of multiple atmospheric phenomena and cannot be accurately categorized under a single hazard (Yang et al., 2025).

Regarding the few consolidated multi-hazard approaches that consider NaTech events, it was recognized that they 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 diverse equipment items to different natural hazards or the characteristics (quantity and type) of dangerous substances stored (Mesa-Gómez et al., 2020). From this observation, the following research question is generated: How can the understanding of context-specific vulnerabilities arising from the complex interaction between industrial critical infrastructures (ICIs) and multi-hazard environments support NaTech risk preparedness?

The accurate efforts to answer the previous question represent the cornerstone for achieving adequate multi-risk NaTech management and strengthening the resilience of industrial infrastructures (Valente et al., 2025). Therefore, a multi-risk framework is developed here to assess the multi-risk NaTech potential of industrial infrastructures. This framework considers the functional and territorial vulnerabilities, following the function-location approach proposed by Castro Rodriguez et al. (2025a). To achieve this, the opportunities critically discussed in previous work to refine the multi-risk NaTech vulnerability indicator originally developed by Pilone et al. (2021) have played a key role. Further discussions on NaTech and multi-risk assessment, limitations, and proposed enhancements of the original indicator are in Castro Rodriguez et al. (2025b).

The key enhancements to strength the multi-risk tool are: i) flexibility in integrating relevant natural factors based on the specific hazards associated with the plant location; ii) introduction of a location priority factor to contextualize the multiple hazards of interest including their cascading effects; iii) use of standardized vulnerability categories for industrial items aligned with data from historical analysis of NaTech events; iv) evaluation of dynamic vulnerability interactions among industrial components, considering their proximity and functional interdependence; v) development of semi-quantitative multi-risk criteria to assess the interaction between hazards and industrial items.

Earlier conceptual work served as a foundation for developing an innovative framework that adapts the Quality Function Deployment (QFD) tool to the multi-risk nature of NaTech events, taking into account the complex interactions between industrial vulnerable elements and multiple natural hazards. This novel framework—Industrial Critical Infrastructure Multi-Risk Deployment (ICI-MRD)—was then tested in an energy-critical infrastructure used as the case study. The methodology to implement the ICI-MRD framework, the example of calculations tested in the case study, and the discussion of its outputs and insights are described in the subsequent sections.

2. The Industrial Critical Infrastructure Multi-Risk Deployment framework (ICI-MRD)

In a nutshell, QFD is a methodology used in product design and development to translate customer needs into specific product features, specifications, and operational characteristics, ensuring customer satisfaction and exceeding expectations throughout the product lifecycle (Geng et al., 2024). QFD assesses how multiple requirements or needs (the so-called “WHATs”) can be met or can be translated into diverse attributes or functions for products, processes, or technologies of interest

("HOWs"), through a conceptual setup known as the House of Quality (HoQ).

QFD was originally introduced in the shipyard industry (Akao, 1972) and was quickly extended and used for the design, improvement, and development of products and technologies in several sectors (Chudjaková and Tobiška, 2017; Geng et al., 2024; Iovan-Dragomir and Luca, 2018; Kowalska et al., 2018; Lee et al., 2017; Lin et al., 2010; Pal et al., 2007). Given the iterative characteristic of the QFD, after establishing the initial House of Quality (HoQ) to identify the primary design needs, the procedure allows the breakdown of the HOWs components, translating the original necessities to a secondary level of design. Subsequently, in the second level, the HOWs are transformed into new WHATs (Castro Rodriguez et al., 2022). The deployment may continue to the third or fourth levels of design (Gutiérrez and de la Vara, 2013).

Over the years, with the rise of sustainability patterns, many developments derived from the original method were introduced, such as QFDE (QFD for the environment), aiming to help engineers with environmental issues (Masui et al., 2003; Younesi and Roghanian, 2015). Further amendments were introduced, such as the introduction of Multi-Criteria Decision Making (MCDM) to weight interaction relationships, strengthening the usability of the QFD tool in complex problems (Sakao, 2007; Ocampo et al., 2020; Song et al., 2020). For instance, Gad El Mola (2025) introduced a fuzzy-QFD-based framework to support green supply chain integration in energy production, incorporating a multi-criteria model to evaluate technical importance and guide operational strategies. Similarly, Babbar and Amin (2018) applied a two-stage QFD and a stochastic multi-objective mathematical model using fuzzy logic to handle uncertainty in environmental decision-making. Al Amin and Baldacci (2024) proposed a novel AHP-integrated QFD-MILP model, enabling prioritization of sustainability challenges and selection of cost-effective solutions through quantitative performance scores.

While research integrating QFD with risk factors and proactive strategies is limited, Wu et al. (2024) combined QFD and failure mode and effect analysis (FMEA) using a compromise solution and interactive MCDM methods to mitigate risks during product upgrades. In addition, Sumrit and Keeratibhubordee (2025) applied a stepwise weight assessment ratio analysis and QFD under the Fermatean fuzzy approach to identify risk factors and proactive strategies in the context of plastic waste recycling. However, as far as the authors are aware, no specific applications to the fields of natural hazards, NaTech, multi-risk analysis, or disaster risk reduction have been made to date. Hence, extracting novel points from the previously described methodologies—particularly the transformation of risk factors into requirement attributes—the ICI-MRD framework introduces a novel adaptation of QFD tailored to the unique characteristics of multi-risk NaTech scenarios.

As illustrated in Fig. 1, this approach transforms the conventional QFD tool into a NaTech-specific framework that explicitly integrates vulnerability assessment across multiple hazards. This adaptation provides a refined and data-driven actionable structure for the multi-risk NaTech vulnerability indicator originally developed by Pilone et al. (2021) and further refinements based on the opportunities discussed in Castro Rodriguez et al. (2025b). The ten steps for implementing ICI-MRD are provided to guide practical application.

2.1. Step 1: Flexible identification of multi-hazards of interest

The multiple hazards to be considered in each specific case study are one of the principal framework inputs. They substitute the WHATs in the traditional QFD method and are placed on the left-side rows (refer to Step 1 in Fig. 1). In the initial method proposed by Pilone et al. (2021), just four fixed categories of natural hazards were considered; therefore, to provide the user with the flexibility to introduce the hazard categories of eventual interest, the classifications for 15 natural factors are adopted (Table 1), divided into four macro-categories according to the criteria of various authors (Gill and Malamud, 2014; Ricci et al., 2021). This flexibility enables the user to focus on the analysis depending on the critical hazards inherent to the location.

It is important to note that the multi-hazard input is not only limited to the natural hazard but also allows the introduction of other categories of interest, for example, aging phenomena or neighboring plant hazards (technological hazards). However, to include additional hazard categories different from natural factors, further research is required to identify the potential cascading effects between the new factors considered.

2.2. Step 2: Multi-hazard cascading interaction

As previously mentioned, multiple hazards relevant to each plant can trigger NaTech events, either directly by initiating a technological

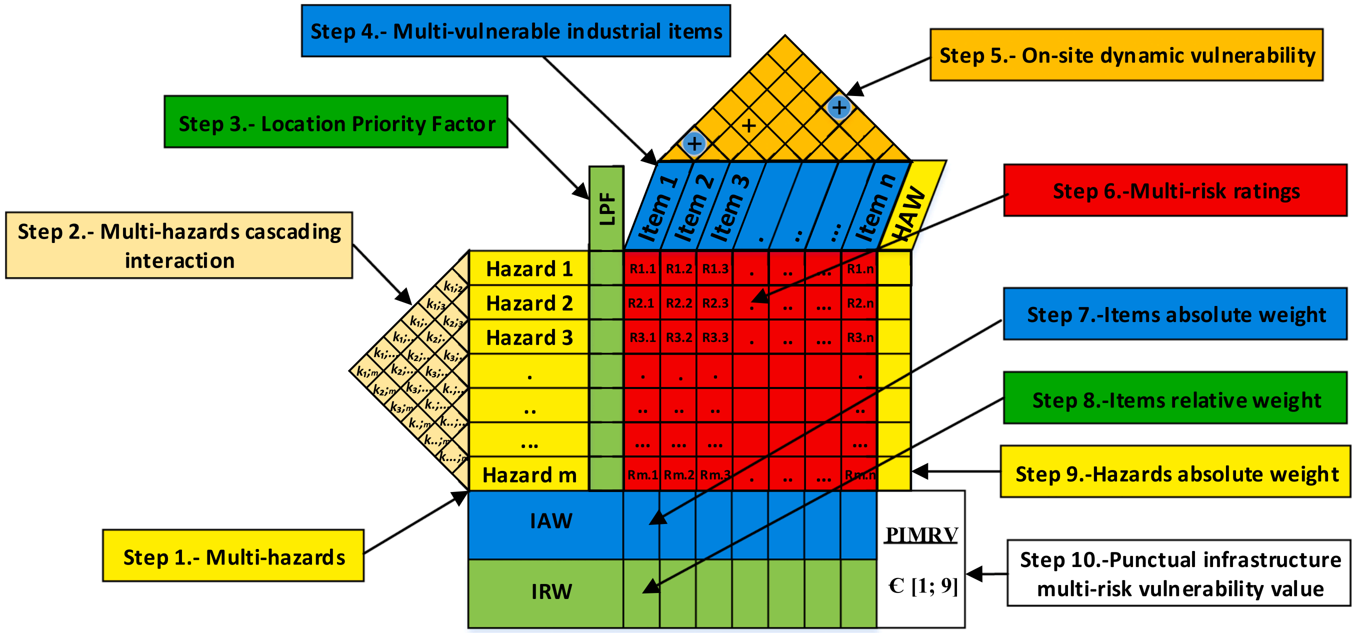

Fig. 1. Framework Industrial Critical Infrastructure Multi-Risk Deployment (ICI-MRD) numbers the steps for its implementation.

Table 1
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 cold temperature (ETc) - Tropical storm (TSt) - Lightning (LN) - Fog (FG)	- Flooding (FL) - Drought (DR) - Wave action (WA)	- Wildfire (WF)

Source: Castro Rodriguez et al. (2025b).

scenario or indirectly through cascading effects involving other natural factors. The initial methodological attempt of the multi-risk NaTech indicator overlooked cascading effects. To capture these interactions, the ICI-MRD framework incorporates a multi-hazard cascading interaction matrix, positioned on the left side of the multiple hazards section, which represents a step further (refer to Step 2 in Fig. 1). This matrix functions as an auxiliary triangular matrix with a side length of "*m*", where *m* represents the maximum number of hazards considered.

Because NaTech events are a specific type of cascading event—natural hazards triggering technological scenarios—in the context of this research, cascading events are defined as follows: (primary natural hazard) → (secondary natural hazard) → (technological scenario). In some cases, the secondary natural hazard can even act as a new initiator factor, potentially triggering additional tertiary hazards (Gill and Malamud, 2017). However, documented cases in the process industry involving more than a secondary natural hazard interaction leading to a NaTech event are rare (Gao et al., 2023). Therefore, the scope of this research focuses on external cascading effects limited to secondary interactions between natural hazards. Next, each interaction between two natural factors is assessed and ranked according to the criteria in Table 2. These rankings, based on a Likert scale from 0 to 3, follow the qualitative criteria for disaster chains between pairs of natural hazards, as proposed by Gill and Malamud (2014) (see **Annex 1**).

The rank obtained for each interaction will feed the single cells within the triangular cascading matrix. Considering the possibility of interchangeable order in the cascading interaction between pairs of hazards in columns and rows in **Annex 1** (i.e. TS→LA or LA→TS), the most critical interaction rank (***$IRHaz_k$***) will be kept regardless of whether it is in the sense **$k_{(i;j)}$** or **$k_{(j;i)}$**. Fig. 2 illustrates not only the simplified notation **$k_{(i;j)}$** for the cascading interaction matrix but also the pathway to assign the interaction weight factor for hypothetical Hazard 1, Hazard 2, and Hazard 3, respectively.

After assigning the ranks within the triangular cascading matrix, the interaction rate is calculated using Eq. 1.

$$IntW_k = \frac{\sum_{i=1}^{m} IRHaz_{k(i;j)}}{3(m-1)} \tag{1}$$

where:

$IntW_k$: Interaction weight factor for each Haz_k concerning the total $k_{(i;j)}$ interactions, $IntW_k \in [0; 1]$.

k: ordinal number assigned to each Haz_k in Table 1 relevant to the industrial context under consideration. $k \in [1; m]$.

m: the maximum number of "k" hazards considered in any specific case.

***$IRHaz_{k(i;j)}$*:** Hazard interaction rank to each cell $k_{(i;j)}$ within the interaction hazard matrix, assigned according to the criteria in Table 2.

$k_{(i;j)}$: every single cell within the interaction hazard matrix where the hazard "k_i" interacts with the hazard "k_j", $i \in [1; m]$; $j = \langle k | k \in [1, m], j \neq i \rangle$.

According to Eq. 1, ***$IntW_k$*** $\in [0, 1]$ except for the case that $m = 1$, where the equation is indeterminate. However, since this equation is designed for interaction between multiple hazards, the analysis of a single hazard is beyond the scope of this methodology, since several specific methodologies exist for this purpose.

2.3. Step 3: Location priority factor to contextualize multi-hazards

One key opportunity to improve the multi-risk NaTech assessment identified in Castro Rodriguez et al. (2025a) is the introduction of a Location Priority Factor (LPF). This LPF not only contextualizes each hazard influence by replacing the previous binary evaluation (0 = absent; 1 = present) with an evaluation of their intensity and extension, but also explicitly accounts for cascading effects. The LPF is in the green column on the right of the multi-hazards column (refer to Step 3 in Fig. 1). Eq. 2 operationalizes the LPF for each hazard under consideration.

$$LPF_k = (Inf_k + IntW_k) \bullet P(NaTech_{MS}|Haz_k) \tag{2}$$

where:

***LFP_k*:** location priority factor for each Haz_k,

***Inf_k*:** influence index of each Haz_k on the industrial context under consideration.

***$IntW_k$*:** Interaction weight factor for each Haz_k (determined by Eq. 1).

$P(NaTech_{MS}|Haz_k)$: Conditional probability of NaTech occurrence in the industrial macro-sector (*MS*) under analysis, triggered by the hazard Haz_k.

Firstly, the interaction weight factor (*$IntW_k$*) (refer to **Section 2.2**) has an additive character, increasing the hazard influence in case of potential cascading effects—$IntW_k \in [0; 1]$. Secondly, the hazard

Table 2
Ranks definition for the multi-hazard cascading interaction.

Rank*(*$IRHaz_{k(i;j)}$*)	Category	Criteria for natural hazards
1	Weak	Where at least one light grey triangle is present in the interacting cell between the pair of natural hazards under concern, indicating that the occurrences are possible even if few cases occurred (see **Annex 1**).
2	Medium	Where both triangles in the interacting cell between the pair of natural hazards under concern are shaded in light grey. Even if a few occurrences are registered, it indicates that the primary hazard could both trigger and increase the probability of a secondary hazard (see **Annex 1**).
3	Strong	Where at least one dark grey triangle is present in the interacting cell between the pair of natural hazards under concern, indicating multiple occurrences of the analyzed interaction (see **Annex 1**).

* When the interacting cell between two natural hazards is left blank, the corresponding rank is 0.

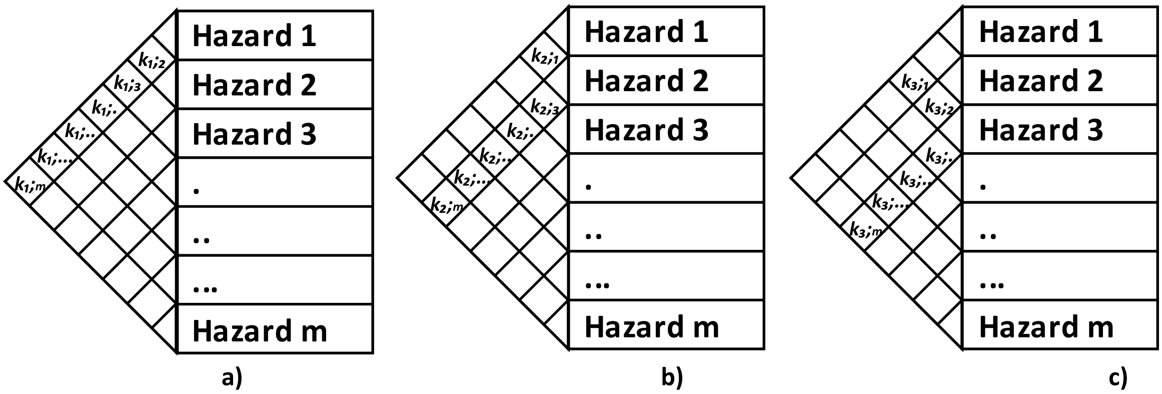

Fig. 2. Details of the notation $Haz_{k(i;j)}$ to each cell within the cascading interaction matrix and pathway considered to calculate the interaction weight factor: a) $IntW_{Hazard\ 1}$; b) $IntW_{Hazard\ 2}$; c) $IntW_{Hazard\ 3}$.

influence (Inf_k) is a key index because it should make risks comparable based on the hazard magnitude, its territorial extension, and the severity of the consequences for the context considered.

In terms of severity, if it is assumed that any considered scenario has the potential to trigger a major accident, then the consequences could be blocked if at least one of the criteria in Annex VI of Directive 2012/18/EU is matched. In a nutshell, this classification is based on specific criteria, including (i) the quantity of hazardous substances, (ii) the severity of injuries to people and damage to real estate, (iii) the immediate or delayed change to the environment, (iv) damage to property, and (v) cross-border damage.

One of the main challenges in defining hazard magnitude is the need for a common metric that allows for the consistent weighting of exposed elements across different hazardous events. To address this, a semi-quantitative rating system applicable to all major risks is required in alignment with the criteria proposed by Suarez-Paba and Cruz (2022). However, assigning ratings to the influence of each hazard on the industrial context requires reliable data to associate accurate categories.

For example, based on hazard indexes from previous research (Krausmann et al., 2011a; 2011b), four ordinal categories have been slightly modified to classify the magnitude ranges of various hazards, such as i) Peak Ground Acceleration (PGA) for earthquakes, ii) lightning density to the ground (Ng) for lightning strikes, and iii) inundation height for floods. The four alert levels used in some European countries to declare cold and heat waves were also considered—refer to Ministero della Salute (2024).

Complementarily, when quantitative data are unavailable, the hazard influence in a specific region can be characterized as discrete events with a specific intensity given a probability in a reference time interval (Marzocchi et al., 2012; Necci and Krausmann, 2022). In addition, ratings can be associated using expert judgment, with the results typically shown as single-vulnerability maps, often scaled from 0 to 1 (Beltramino et al., 2022). Territorial vulnerability classes can then be applied to assign ratings to the influence of each hazard (Castiglione et al., 2025; Castro Rodriguez et al., 2023).

Table 3 presents the ordinal scale and corresponding categorical hazard classification for Inf_k based on the available magnitude ranges of selected natural hazards. Additionally, the last column links four territorial vulnerability classes to the hazard index ordinal scale. Further research is required to associate the influence index with the magnitude ranges of other hazard factors in Table 1.

Referring to Eq. 2, the third element $P(NaTech_{MS}|Haz_k)$ can be determined from historical analysis when data is available. Further details about how to determine this data can be found in previous research analyzing natural factors such as lightning, cold, and heat waves (Castro Rodriguez et al., 2024; Krausmann et al., 2011a; Ricci et al., 2023a; 2023b). On the other hand, in the absence of data or adopting an extreme criterion, the occurrence of NaTech events given the macro-sector of concern may be considered certain, assuming $P(NaTech_{MS}|Haz_k) = 1$; in this case, Eq. 2 is simplified as Eq. 2*.

Table 4
Proposal of harmonized categories of equipment, codes, and descriptions.

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

Source: Castro Rodriguez et al. (2025b).

Table 3
Influence index and classifications based on magnitude ranges of available factors or spatial analysis.

Influence index (*Inf_k*)	**Hazard classification**	**PGA range,** m s^{-12} (50-yr exceedance probability)	***Ng*** (I > 3 kA), $km^{-2}\ y^{-1}$	**Inundation height,** m	**Hot and cold waves**	**Territorial vulnerability index (TV)** $tv \in [0; 1]$
1	Low	≤ 0.8	< 0.25	$h < 0.1$	Level 0	$0 \leq tv < 0.3$
2	Moderate	0.8–2.4	0.25–2	$0.1 \leq h < 0.5$	Level 1	$0.3 \leq tv < 0.6$
3	High	2.4–4.0	2–8	$0.5 \leq h < 1$	Level 2	$0.6 \leq tv < 0.9$
4	Critical	> 4.0	> 8	$h \geq 1$	Level 3	$tv \geq 0.9$

$$LPF_{k^*} = (Inf_k + IntW_k) \tag{2*}$$

where $\boldsymbol{LFP_{k^*}}$ is the location priority factor simplified for each Haz_k (assuming $P(NaTech_{MS}|Haz_k) = 1$).

2.4. Step 4: Multi-vulnerable industrial Items

Another important input to implement the classical QFD is the definition of HOWs, which in the ICI-MRD framework are adapted to each of the "*n*" multi-vulnerable categories of exposed industrial items (refer to Step 4 in Fig. 1). Instead of the six classes of vulnerable items considered in the initial methodology, this framework expands the consideration to eleven equipment categories, ensuring consistency with available research on NaTech historical analysis (Table 4). The new categories not only support the data-driven multi-risk assessment but also provide the flexibility to choose the infrastructural items of interest in each case study. More discussion about the adopted categories for vulnerable items can be found in Castro Rodriguez et al. (2025b).

2.5. Step 5: On-site dynamic vulnerability among the industrial items

As discussed in Castro Rodriguez et al. (2025b), the impact of a hazard on internal industrial infrastructure could increase its dynamic vulnerability, amplifying the possibilities for the on-site domino effects.

Regarding this, the multi-vulnerable interaction matrix (refer to Step 5 in Fig. 1) is a novel improvement of the ICI-MRD framework regarding the previous stage of the multi-risk NaTech methodology. This triangular matrix, known as the roof of HOWs in the classical QFD, is at the top of the HoQ. This approach enables the identification of internal interactions not only considering the spatial proximity of each industrial item in the plant layout but also its functional interconnections, as well as the emergency-response scenarios defined in the response plans (Ricci et al., 2024). The fieldwork, plant drawings, process schemes, scenario analysis, simulation, geospatial information available, inherent safety distances, substance characterization, and identification of escalation vectors could be very helpful in identifying dynamic vulnerability relationships.

At the current early stage of this methodological part, the qualitative criterion with the symbology ⊕ (very strong positive) and + (strong positive) is adopted to assess the direct potential interactions. When the interaction is not contemplated, the cell is left blank. Even if not discarded, the inverse interactions conceived in the classical QFD method [very strong negative (–) and strong negative (-)], are less probable for the ICI-MRD framework, given the recognized interdependence between processes, equipment, and industrial facilities (Gutiérrez and de la Vara, 2013; Jain et al., 2017).

Further elaborations are required to take a step further from the current qualitative on-site dynamic vulnerability evaluation in the ICI-MRD framework to the application of a quantitative index introducing the inherent safety perspective in the prevention of domino effects (Cozzani et al., 2009, 2007; Tugnoli et al., 2008a, 2008b). The need for specific methodologies for domino effects in NaTech scenarios, as highlighted by Cozzani et al. (2014), should be aligned with the ICI-MRD framework, considering also the pros and cons of the available approaches for modeling and managing domino effects in the process industry (Chen et al., 2020). There are probabilistic models to assess domino escalation tailored to single natural factors such as lightning (Misuri et al., 2020) or floods (Zeng et al., 2021), but applications aligned to all the natural factors in Table 1 are yet to be required. In addition, the resilience-based approach should be integrated to support the preparedness of NaTech domino effects in chemical industrial clusters (Chen et al., 2022; Tan et al., 2024), including the uncertainty consideration in the linkage of natural disasters and technical accidents (Xu et al., 2023).

Table 5

Multi-risk ratings and descriptions for the interactions between hazards and items.

MRI ratings[*]	Saaty scale/ historical frequency	Frequency based on historical analysis	Without data (through voting or multi-voting of experts)
1	Minor importance/ Remote	$0 \leq P(NaTech) < 0.1$	The dynamic of the event is considered impossible or rare. Neither references nor reports are available.
3	Moderate importance/ Unlikely	$0.1 \leq P(NaTech) < 0.2$	The dynamic of the events is considered possible without documentary support.
5	Strong importance/ Possible	$0.2 \leq P(NaTech) < 0.3$	Qualitative references[**] recognize the interaction, but just a small number of occurrences are reported.
7	Critical importance/ Likely	$0.3 \leq P(NaTech) < 0.6$	Qualitative references recognize the interaction, large number of occurrences are reported.
9	Highly Critical importance/ almost certain	$0.6 \leq P(NaTech) < 1$	
2, 4, 6, 8	Intermediate values can be used in case differences are appreciated in the assessment process.		

[*] MRI ratings are represented as $R_{m.n}$ for reasons of space in the cells of the interaction matrix (see Step 6 in Fig. 1).

[**] Qualitative references to identify interactions can be found in Tables 2 and 3 of Necci and Krausman (2022).

2.6. Step 6: Multi-risk interaction ratings between hazards and infrastructure

A key improvement to the initial multi-risk NaTech indicator proposed by Pilone et al. (2021) is the incorporation of data-driven criteria derived from historical analyses of NaTech-triggered events across eight macro-sector categories within the process industry aligned with the categories of Casson Moreno et al. (2018). This enhancement enables a more precise assignment of ratings between vulnerable industrial elements and the natural hazards (see Step 6 in Fig. 1), refining the previous binary evaluation.

Currently, data is available for natural factors such as lightning and extreme temperatures (hot and cold waves) (Castro Rodriguez et al., 2024; Ricci et al., 2023a, 2023b). This data aligns with retrieval assumptions, including macro-sector categories (Casson Moreno et al., 2018) and the classification of industrial events—accidents, incidents, and near misses (Rathnayaka et al., 2011). Additionally, past research on flood-triggered NaTech events in the process industry (Cozzani et al., 2010) provides quantitative insights into multi-risk interactions for some macro-sector categories. However, as detailed data is still lacking for other natural hazards listed in Table 1, qualitative criteria offer a practical alternative to support the assignment of multi-risk ratings within the ICI-MRD framework.

Table 5 presents a rating system for the multi-risk interactions (MRI) based on the 1–9 Saaty scale, commonly used in the Analytical Hierarchy Process (AHP) (Goepel, 2019; Saaty, 1990; Zhang et al., 2009). This system is adapted to evaluate the importance and frequency, reflecting on cases without historical data.

2.7. Step 7: Items absolute weight

Once all the inputs in the ICI-MRD framework have been defined, it is time to operationalize the output determination. Specifically, the determination of the items absolute weights (refer to Step 7 in Fig. 1**)** remains quite like the original method of Pilone et al. (2021). It consists of totalizing the multiple superposed hazard interactions on each vulnerable item (single column). Therefore, the items absolute weights represent the multi-functional vulnerability of each industrial item exposed to the multiple hazards in its location. Eq. 3 presents the way to determine the absolute weight of each item:

$$IAW_e = \sum_{k=1}^{m} MRI_{k;e} \tag{3}$$

where:

***IAW*$_e$:** absolute weight of each item category "*e*", with $e \in [1; n]$.

***n*:** the maximum number of categories of items/equipment considered.

***MRI*$_{k;e}$:** multi-risk interaction between each single hazard on each vulnerable item (obtained from Table 5).

2.8. Step 8: Items relative weight

The relative weight of each item constitutes a novelty in the ICI-MRD framework (refer to Step 8 in Fig. 1**)**. It incorporates not only the multi-functional vulnerabilities described in **Section 2.7** but also affects them by the contextualized territorial vulnerabilities. This is achieved by multiplying the location priority factor (LPF) with the value assigned to each multi-risk interaction cell ($MRI_{k;e}$). Eq. 4 presents the method for calculating the relative weight of items.

$$IRW_e = \sum_{k=1}^{m} MRI_{k;e} \times LPF_k \tag{4}$$

where:

***IRW*$_e$:** relative weight of each item category "*e*".

***LFP*$_k$:** the same as determined in Eq. 2.

2.9. Step 9: Hazard absolute weight

The hazards absolute weight (refer to Step 9 in Fig. 1**)** is determined by summing the interaction of each single hazard "*k*" on the multiple vulnerable items category under concern (single row). In this way, the hazards dangerousness can be ranked across the multi-vulnerability of the equipment categories. This is another novel element of the ICI-MRD framework. Eq. 5 presents the determination of the hazard absolute weights.

$$HAW_k = \sum_{e=1}^{n} MRI_{k;e} \tag{5}$$

where:

***HAW*$_k$:** absolute weight of each hazard category "*k*" across the multi-vulnerability of the equipment categories ($k \in [1; m]$).

Furthermore, future challenges are identified in developing a hazard relative weight (***HRW*$_k$**) that incorporates a Coping Capacity Factor (***CCF***)—not yet operationalized—to gauge the system overall preparedness against the analyzed multi-hazard scenarios. Conceptually, the CCF should encompass elements such as inherent safe-by-design features, layered safety barriers, routine maintenance protocols, emergency response plans, and integration with land-use and urban-planning coordination, among others.

2.10. Step 10: Punctual infrastructure multi-risk value

To determine the overall multi-risk NaTech vulnerability of the single facility, the punctual infrastructure multi-risk value (*PIMRV*) represents a novel decision criterion (refer to Step 10 in Fig. 1). This value represents a ratio where the numerator represents the multi-risk interactions of technical features to the different contextualized hazards, while the denominator represents its hypothetical maximum value for the maximum influence of the contextualized hazards on the vulnerable items considered (refer to Eq. 6**)**.

$$PIMRV = \frac{\sum_{e=1}^{n} IRW_{e\,max}}{m \times n \times LPF_{k\,max}} \tag{6}$$

where:

***PIMRV*:** punctual infrastructure multi-risk value—$PIMRV \in [1; 9]$.

***m*:** the maximum number of "*k*" hazards considered in any specific case.

***n*:** the maximum number of items/equipment categories considered.

***IRW*$_{e\,max}$:** IRW_e value substituting in Eq. 4 the LPF_k* defined in Eq. 2*.

***LPF*$_{k\,max}$:** *is the maximum possible value for the* LPF_k*defined in Eq. 2*, assuming Inf_{kmax} and $IntW_{kmax}$ for each hazard *k*.

Substituting, the $IRW_{e\,max}$ is determined by Eq. 7**,** while $LPF_{k\,max}$ is determined by Eq. 8.

$$IRW_{e\,max} = \sum_{k=1}^{m} MRI_{k;e} \times LPF_{k^*} \tag{7}$$

$$LPF_{k\,max} = (Inf_{k\,max} + IntW_{k\,max}) \tag{8}$$

where:

$Inf_{k\,max} = 4$ according to the rating system in Table 3.

$IntW_{k\,max} = 1$, since $IntW_k \in [0; 1]$, (in the case of multi-hazard scenarios, where $m>1$)

A key methodological enhancement that the ICI-MRD framework offers concerning the final assessment is the dynamic character of PIMRV concerning the previous static metric in the initial method proposed by Pilone et al. (2021). Therefore, the *PIMRV* final value is not conditioned by the number of hazards (*m*) or item categories (*n*) that are analyzed in each case study. The PIMRV determination provides an early warning indicator on NaTech potential, aligned with the function-location approach addressing NaTech vulnerabilities in industrial multi-hazards contexts (Castro Rodriguez et al., 2025a). Five categories of importance/priority according to Table 5 are associated with the final value of *PIMRV*, which ranges from 1 to 9 (see Fig. 3**)**. These categories have implications for the spatial vulnerability mapping of industries represented as punctual critical infrastructures at a primary decision-making level.

The categories shown at the top of Fig. 3 align with operational guidance and established criteria in NaTech research (Krausmann et al.,

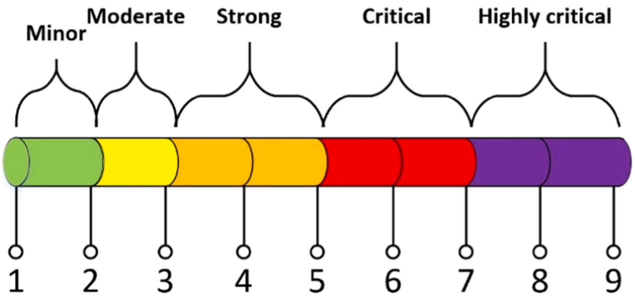

Fig. 3. Scale of priority for PIMRV values.

2011; Suarez-Paba and Cruz, 2022). The associated thresholds range from broadly acceptable NaTech risk for the "Minor" priority, where NaTech-specific fieldwork and routine inspections should be implemented, to intolerable risk for the "Highly critical" category, where regulatory interventions should be carried out to limit the industrial activity in the specific location.

On the other hand, intermediate priority categories correspond to varying levels of required risk management actions. For instance, for "Moderate" priority, it remains essential to analyze the intermediate outputs of the ICI-MRD, as the criticalities identified through data-driven multi-risk assessment may provide valuable insights for improving both on-site and off-site emergency protocols (Zheng et al., 2024). The documentary improvement should be combined with fieldwork and extraordinary inspections.

For the "Strong" priority category, interventions must not only include actions from the lower categories but also focus on reinforcing safety barriers (active, passive, and procedural), based on vulnerability-centered outputs (Di Maio et al., 2023a, 2023b; Misuri et al., 2023). In the case of "Critical" priority, all previous intervention actions should be included, with an added emphasis on retrofitting assets (Cruz et al., 2017; Necci and Krausmann, 2022), to enhance the facility robustness to natural challenges specific to its location.

Although the stakeholders highly appreciate punctual decisions such as PIMRV, the method does not discard the necessity of going deeper with specific analysis, according to the scale of priority of PIMRV.

To support a more in-depth vulnerability-centered analysis, when scores fall within the "Strong" or "Critical" categories, further deployments to more specific levels of design are highly encouraged.

2.11. ICI-MRD framework: Deployment to the next level of design

The ICI-MRD framework offers valuable extra advantages to develop strategies in case PIMRV is associated with "Strong" or Critical priorities. Building on the intermediate outcomes such as HAW_k and IRW_e, the iterative nature of the QFD tool, previously introduced at the beginning of this **Section 2**, allows for deeper analysis. For instance, in the next level of deployment, the vulnerable elements—represented as blue columns in Fig. 1—are transposed in the rows of a second-level matrix as design requirements, while the relative weights (IRW_e) of the first-level ICI-MRD established the new priorities for the new WHATs (Fig. 4**)**.

This is an iterative process aiming to develop engineering requirements for designing protection layers, aligning them with the contextualized rankings of the vulnerable elements. This ensures that criticalities are assessed based on the territorial characteristics of the plant location. Similarly, prevention layer requirements and their associated rankings can be expanded into a third design level to define the features of site-specific devices, barriers, and safety measures designed to account for the effects of multi-hazard events on their performance, ensuring they can effectively prevent or mitigate accidents, according to Di Maio et al. (2023a). The refinements can continue till obtaining the final output of this vulnerability-centered iterative design procedure, which consists of a master plan for resource allocation and implementation, aiming to strengthen preparedness to face natural disruptions in the short term. This deployment analysis may be enhanced through the integration of focalized multiparametric resilience assessments that monitor real-time process changes and single protection layers (Sun et al., 2025).

3. Case study: example of calculations for the ICI-MRD framework

This section illustrates the calculations for each step of the ICI-MRD framework highlighted in Fig. 1, applied to a critical energy infrastructure case study. Consequently, the subsections correspond to the steps described in **Section 2**. The industrial plant used here as a case study is a thermoelectric plant (Fig. 5), considered a critical energy infrastructure, considering Directive (EU) 2022/2557.[1] The plant unitary operations are both chemical and physical.

The activities include utilities necessary for the production plant operation, such as compressed air production, wastewater treatment, steam production, and warehousing. As elements inherent to the plant processes, the following equipment was identified: atmospheric storage tanks, tall structures such as chimneys and process columns and equipment, heat exchangers, complex systems of pipelines, complex electrical networks, water treatment components, and storage of raw materials. For more details about the plant description and individual analysis of its territorial vulnerability and the critical factors, see Castro Rodriguez et al. (2025a).

3.1. Identification of hazards

Four natural hazard factors were considered as input for the analysis. Among them, the hydrological factor—specifically flooding—was identified as the most critical for the industrial context under study. In contrast, geophysical and climatological hazards such as earthquakes and wildfires were excluded, as the case study site shows very low exposure to these events. Further details on the vulnerability of the infrastructure to multiple surrounding hazards are provided in Castro Rodriguez et al. (2025a). Additionally, three meteorological factors were included, as they account for approximately 25 % of NaTech events reported in the process industry (Ricci et al., 2021).

The four hazard factors considered are i) lightning (LN), ii) extreme temperature hot (ETh), extreme temperature cold (ETc), and flooding (FL).

3.2. Determination of multi-hazard cascading interaction

As concerns the present case study, the only potential cascading effect was registered for the heat waves causing flooding phenomena (Eth→FL). According to the criteria in Table 2 and **Annex 1**, $IRHaz_{(Eth;FL)} = 3$. Then, the corresponding interaction weighting factor is determined by substituting into Eq. 1.

$$IntW_k = \frac{\sum_{i=1}^{m} IRHaz_{k_{(i;j)}}}{3(m-1)} = IntW_{Eth} = \frac{IRHaz_{(Eth;FL)}}{3(4-1)} = \frac{3}{3\times 3} = 0.33 \tag{1a}$$

3.3. Determination of location priority factor

To calculate the LPF, Eq. 2 should be determined for each Haz_k. Table 6 offers the necessary information for the contextualized four hazards under consideration. This information includes the previously determined $IntW_k$, the Inf_k selected from column 1 in Table 3**,** and the conditional probability of NaTech events in the macro-sector power production ($MSpp$) available from previous work (Castro Rodriguez et al., 2024; Cozzani et al., 2010; Ricci et al., 2023a, 2023b).

By substituting in Eq. 2, the LPF_k is determined as follows:

$$LFP_{LN} = (Inf_{LN} + IntW_{LN})\times \mathrm{P}(NaTech_{MSpp}|Haz_{LN}) = (3+0)\times 0.06 = 0.18 \tag{2a}$$

$$LFP_{Eth} = (Inf_{Eth} + IntW_{Eth}) \times \mathrm{P}(NaTech_{MSpp}|Haz_{Eth}) = (3+0.33)\times 0.044 = 0.14 \tag{2b}$$

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

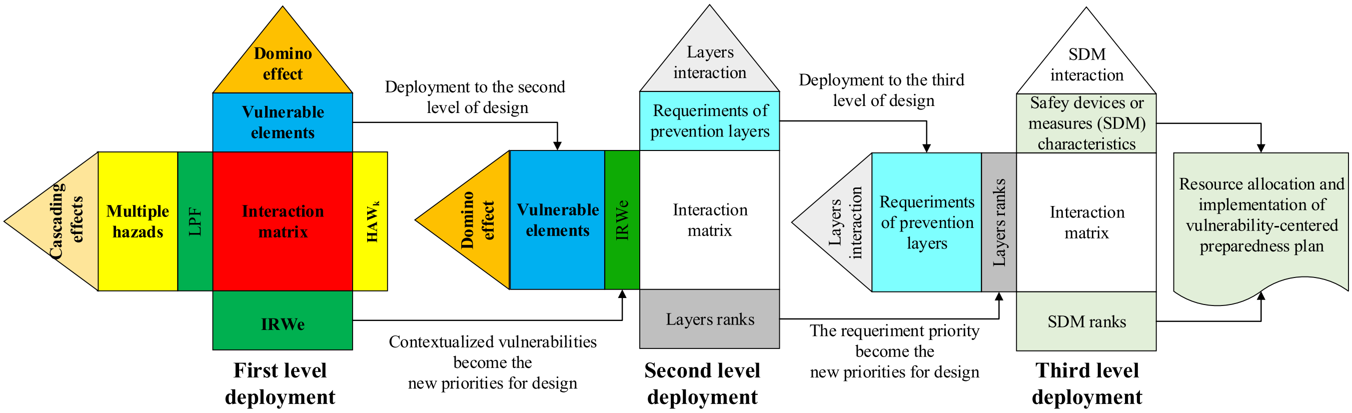


Fig. 4. Representation of the deployment process to an in-depth level of vulnerability-centered design.

Fig. 5. Satellite view of the energetic critical infrastructure used as a case study. Source: (Castro Rodriguez et al., 2025a).

$$LFP_{Etc} = (Inf_{Etc} + IntW_{Etc}) \times \mathrm{P}(NaTech_{MSpp}|Haz_{Etc}) = (4+0) \times 0.058 = 0.17 \tag{2c}$$

$$LFP_{FL} = (Inf_{Fl} + IntW_{Fl}) \times \mathrm{P}(NaTech_{MSpp}|Haz_{Fl}) = (4+0) \times 0.01 = 0.04 \tag{2d}$$

3.4. Selection of multi-vulnerable items

Since underground storage deposits (USD) are not present in the case study, this category was disregarded, as well as the categories road/rail tanker (TK) and auxiliary systems and their utilities (ASU). The remaining categories proposed in **Section 2.4** were considered.

3.5. Identification of on-site dynamic vulnerability

As described in **Section 2.5**, this analysis is qualitative, based on potential dynamic scenarios and spatial criteria, considering not only the industrial item proximity but also their functional interconnections. Fig. 6 outlines key facilities in the plant layout to highlight potential direct interactions during on-site technological scenarios, enabling the completion of the multi-vulnerability interaction matrix. This is a simplified first attempt to operationalize the on-site dynamic vulnerability within the ICI-MRD framework. Spatial elaborations are highly recommended to increase the awareness of dynamic vulnerability and visualize relationships and potential superposition of impacted facilities or equipment (Castro Rodriguez et al., 2025a).

Table 6
Input variables to determine the LPF of the industrial context of concern.

Multi-hazards	Inf_k	$IntW_k$	$\mathrm{P}(NaTech_{MSpp}\|Haz_k)$
1.-LN	3 (High)	0	0.06
2.-ETh	3 (High)	0.33	0.044
3.-ETc	4 (Critical)	0	0.058
4.-FL	4 (Critical)	0	0.01

As discussed in the methodological section, a systematic integration of domino effect criteria would refine the quantitative operationalization of the method, considering the various available approaches for modeling and managing domino effects in the process industry, summarized in Chen et al. (2020).

3.6. Multi-risk rating assignments

The multi-risk evaluation shown in Table 7 was carried out according to the criteria in Table 5.

Specifically, the quantitative data for some vulnerable equipment categories were found in previous research about historical NaTech analysis in the process industry (Castro Rodriguez et al., 2024; Cozzani et al., 2010; Ricci et al., 2023a, 2023b). Alternatively, when data is unavailable for the item under analysis, the qualitative criteria offer a suitable solution for decision-making. When there is quantitative evidence, it prevails as a criterion.

3.7. Determining the item absolute weight

Once the multi-risk interaction between each single hazard on each vulnerable item is assigned, then each IAW_e is determined by substituting in Eq. 3. The calculations can be consulted in **Annex 2.1**.

3.8. Determining the item relative weight

Similarly, the item relative weight was determined by substituting in Eq. 4 (see **Annex 2.2** for calculations).

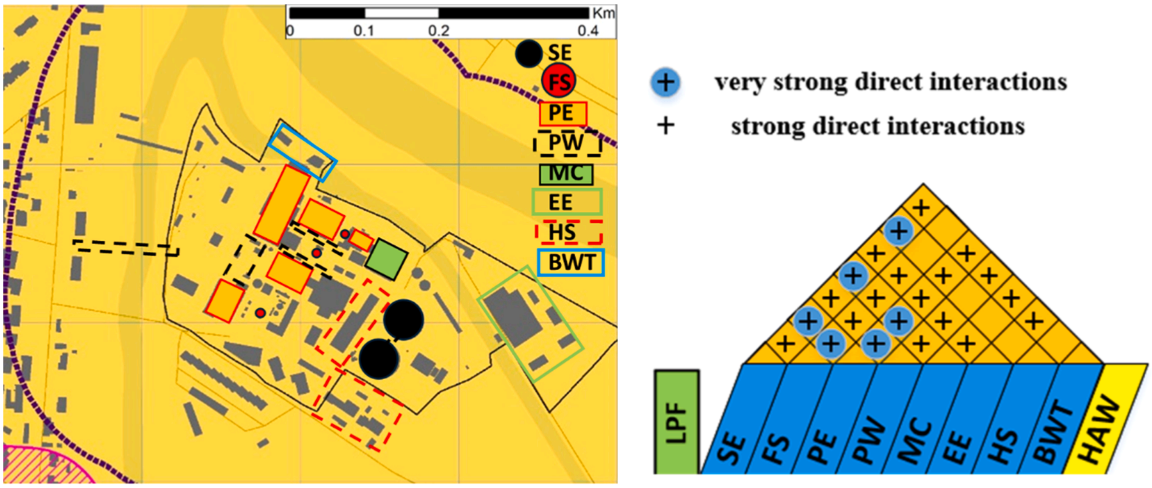


Fig. 6. On-site dynamic vulnerability analysis. a) Principal industrial items representation in the plant layout. b) Triangular matrix interaction for the vulnerable elements (roof). Legend: SE: Storage equipment. FS: Flare stakes. PE: Process equipment PW: Pipework. MC: Machinery. EE: Electrical equipment and electronic devices. HS: Other hazardous storage. BWT: Basins and water treatment elements.

Table 7
Multi-risk evaluation for hazards and items.

Hazard	Criteria	SE	FS	PE	PW	MC	EE	HS	BWT
1. LN	Quantitative	0.48	0.01	0.05	0.08	0.08	0.26	-	-
	Qualitative	-	-	-	-	-	-	4	2
	$MRI_{LN;e}$	**7**	**1**	**2**	**2**	**2**	**5**	**4**	**2**
2. ETh	Quantitative	0.299	-	0.024	0.049	0.064	0.039	0.313	-
	Qualitative	-	1	-	-	-	-	-	2
	$MRI_{ETh;e}$	**5**	**1**	**1**	**1**	**2**	**1**	**5**	**2**
3. ETc	Quantitative	0.127	-	0.066	0.387	0.036	0.141	-	-
	Qualitative	-		-	-	-	-	1	4
	$MRI_{ETc;e}$	**3**	**2**	**2**	**7**	**1**	**3**	**1**	**4**
4. FL	Quantitative	0.686	-	0.054	0.17	0.04	-	0.017	-
	Qualitative	-	1	-	-	-	3	-	9
	$MRI_{EL;e}$	**8**	**1**	**2**	**3**	**1**	**3**	**1**	**9**

3.9. Determining the hazards absolute weight

Likewise, the hazard absolute weight was determined by substituting in Eq. 5 (see **Annex 2.3** for calculations).

3.10. Determining the punctual infrastructure multi-risk value

To determine the PIMRV, firstly, the LPF_{k^*} is determined for the four hazards under consideration as defined in Eq.2* (see Table 8).

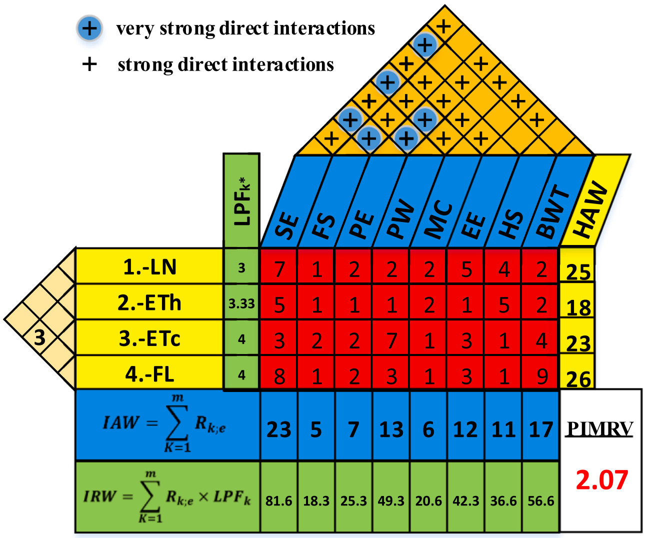
With the previous values, the IRW_{emax} is obtained by substituting in Eq.7 (see **Annex 2.4** for calculations).

Finally, $PIMRV$ can be determined by substituting into Eq. 6.

$$PIMRV = \frac{\sum_{e=1}^{n} IRW_{emax}}{m \times n \times LPF_{kmax}} = \frac{81.65+18.33+25.33+49.33+20.66+42.33+36.65+56.66}{5\times4\times8} \approx 2.07 \tag{6a}$$

Table 8
Values of LPF_{k^*} for the four hazards considered.

LPF_{LN^*}	LPF_{Eth^*}	LPF_{Etc^*}	LPF_{FL^*}
3	3.33	4	4



	LPF_{k^*}	SE	FS	PE	PW	MC	EE	HS	BWT	HAW
1.-LN	3	7	1	2	2	2	5	4	2	25
2.-ETh	3.33	5	1	1	1	2	1	5	2	18
3.-ETc	4	3	2	2	7	1	3	1	4	23
4.-FL	4	8	1	2	3	1	3	1	9	26
$IAW = \sum_{K=1}^{m} R_{k;e}$		23	5	7	13	6	12	11	17	PIMRV
$IRW = \sum_{K=1}^{m} R_{k;e} \times LPF_k$		81.6	18.3	25.3	49.3	20.6	42.3	36.6	56.6	2.07

Fig. 7. Output of the ICI-MRD framework tested on an energetic critical infrastructure.

4. Results and discussion

The final output for the ICI-MRD framework is shown in Fig. 7, illustrating the multi-risk NaTech evaluation for the potential impacts of

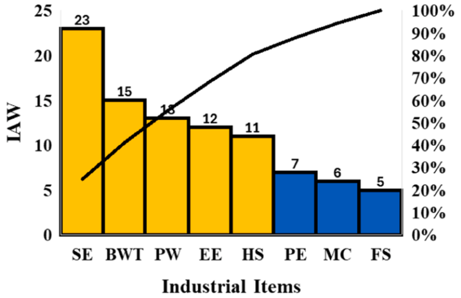


Fig. 8. Pareto diagram for individual items multi-vulnerability (IAW).

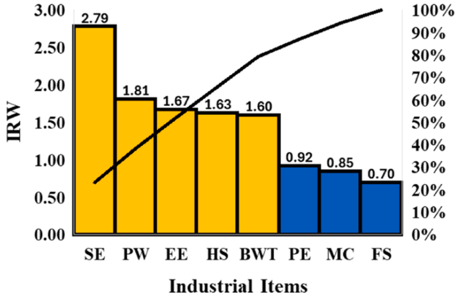


Fig. 9. Pareto diagram for items individual function-location multi-vulnerability (IRW).

four natural hazards on eight industrial items belonging to an energetic critical infrastructure.

In the present case, the *PIMRV* is rounded to 2.07, considering the four hazards threatening all the industrial items. This metric falls into "moderate" priority—closer to minor importance than to strong (refer to **Section 2.10**). According to the management actions, the singular analysis of intermediate outputs in the ICI-MRD framework was carried out in order to update the emergency protocols based on data-driven decision-making.

For instance, it can be appreciated in Fig. 7 the presence of two triangular matrices, each representing potential cascading effects separately. The left triangle shows just the strong interaction ETh→FL. On the other hand, the roof triangle matrix shows, in general, strong interaction among the items, with implications for domino effects. For example, it can be seen how SE and PE, according to their position and functions, compromise all the rest of the equipment categories with strong and very strong direct relationships with all the elements. Likewise, the rest of the items in case of failure might impact spatially or by function the entire process plant.

IAW highlights the multi-vulnerability of each item to the superposed multiple hazards considered (Fig. 8).

It can be seen how the bars in yellow accumulate 80 % of the multi-vulnerability of the plant. Just the "storage equipment" and the "water treatment basins" account for around 40 % of the total weight. It is important to note how items such as PE, previously highlighted with strong on-site dynamic vulnerability in case of disasters, receive an IAW of moderate importance regarding other items with less dynamic vulnerability, such as HE.

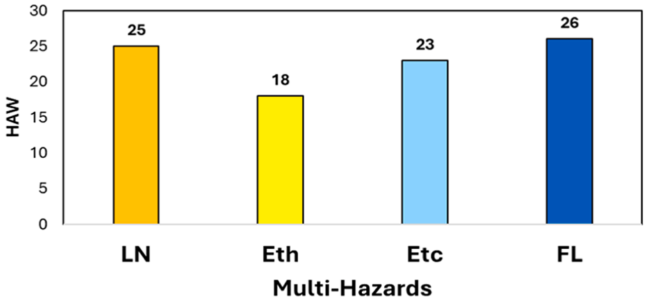


Fig. 10. Dangerousness of each hazard against the critical infrastructure as a punctual element.

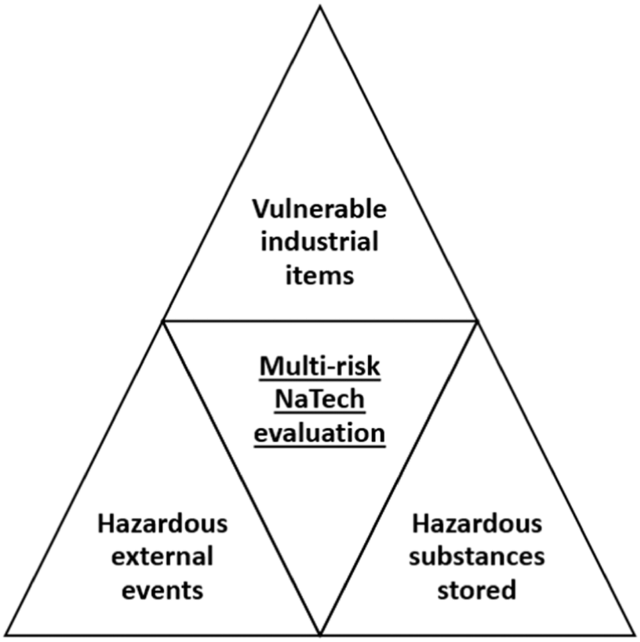


Fig. 11. Theoretical conception of the multi-risk NaTech vulnerability indicator. Source: (Castro Rodriguez et al., 2025b).

Analogously, Fig. 9 shows the multi-risk analysis focusing on each single item but including the contextualized location priority factor (LPF_k). For the calculations, refer to **Annex 2.2**.

It is important to note how the item ranking changes when the vulnerability is contextualized to the specific plant location. For instance, BWT passed from second place to fifth compared to Figs. 8 and 9.

The conditional probability of NaTech in the power production macro-sector is low for the considered hazards; in consequence, it has an influence on the LPF_k and the contextualized items multi-vulnerability. A second approach may be substituting the LPF_{k^*} and adopting a more cautious strategy (refer to **Section 3.10 and** Fig. 7).

Moving to the hazards absolute weight (*HAW*), this column offers the integrated dangerousness of each hazard analyzed concerning all the integrated items (Fig. 10).

The final *HAW* values are the sum of the contributions of various items (in this case, 8), meaning it depends on the number of items involved. The key aspect of this analysis is that it allows for ranking hazards that overlap within the same industrial context regarding the items analyzed in any case. Differences in the dangerousness of considered hazards can be appreciated, contributing to increasing awareness and having direct implications for achieving resilience by introducing corrective measures according to the importance of the hazard.

5. Conclusions and implications

This research presents an innovative adaptation of the tool Quality Function Deployment, aiming to address opportunities to enhance the multi-risk assessment of NaTech vulnerabilities of industrial infrastructures. Then the Industrial Critical Infrastructure Multi-Risk Deployment framework was here consolidated, which fully looks at how multiple hazards in areas around industrial critical infrastructures can affect different functional industrial items.

The ICI-MRD framework was tested in an energetic critical infrastructure as a case study, which looked at how flooding, lightning, and both extreme temperatures (cold and hot) might affect eight categories of industrial items. A punctual infrastructural multi-risk value was calculated as a useful metric for ex-ante multi-risk assessment of the NaTech potential of critical infrastructures. In the tested case, the *PIMRV* resulted in 2.07 falling in the category of moderate priority. Consequently, the analysis of intermediate outputs in the ICI-MRD framework was carried out to update the emergency protocols based on data-driven decision-making.

Hence, the exact weight of each item was determined considering the superposed effects of the four hazards. In the tested case, water treatment basins and storage equipment account for around 40 % of the total weight. However, the industrial items rank changes when the multi-risk ratings were contextualized through the location priority factor. On the other hand, the absolute weight for the four considered hazards provided a rank for hazard dangerousness, considering their influence on the total vulnerability of industrial items. Both the vulnerable items and the rank for hazards raise awareness by providing data-driven decision-making in order to introduce accurate strategies to support the preparedness of both industrial plants and the territory.

While the PIMRV metric represents a useful early warning at primary decision-making levels, it also offers risk management actions dictating deeper analysis of intermediate outcomes or further deployments. In contrast to the tested case, when the outcomes dictate higher levels of priority, deployment to a deeper level of analysis shall be conducted, aiming to obtain the master plan of major interventions to mitigate the impacts of natural hazards through the enhancement of barriers, retrofitting industrial equipment, and strengthening the emergency response plans.

Further case studies are needed to advance the ICI-MRD framework to the next design levels and validate the framework's adaptability across hazard combinations. Additionally, ongoing efforts aim to develop a coping capacity factor (CCF) to evaluate how well each vulnerable item withstands multiple surrounding hazards, incorporating a hazard relative weight (HRW) similar to the current item relative weight (IRW).

The multi-risk NaTech interactions between the infrastructure and territory here operationalized through the ICI-MRD framework should be expanded by integrating a new index to assess major industrial accidents based on hazardous substance criteria. This index, developed in line with European regulations, includes both Seveso and non-Seveso facilities (Castro Rodriguez et al., 2025c). This integration shall complete the theoretical conception of multi-risk NaTech evaluation as conceptualized in Fig. 11.

Moreover, more research is essential to better understand multi-risk interactions between less-studied natural factors and industrial plants, as well as to improve the accuracy of natural hazard characterization. Enhancing real-time data capture through advanced monitoring devices will further support more informed decision-making.

Finally, while ICI-MRD was initially tested in industrial infrastructures, this methodological framework could be generalized to other types of critical infrastructures (CI). However, further cross-disciplinary research is needed to identify clusters of items specific to each type of CI and to tailor criteria for multi-risk assessment.

Ethics statement

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

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CRediT authorship contribution statement

DEMICHELA Micaela: Writing – review & editing, Supervision, Resources, Data curation, Conceptualization. **BARRESI Antonello A.:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Data curation. **David Javier Castro Rodriguez:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

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

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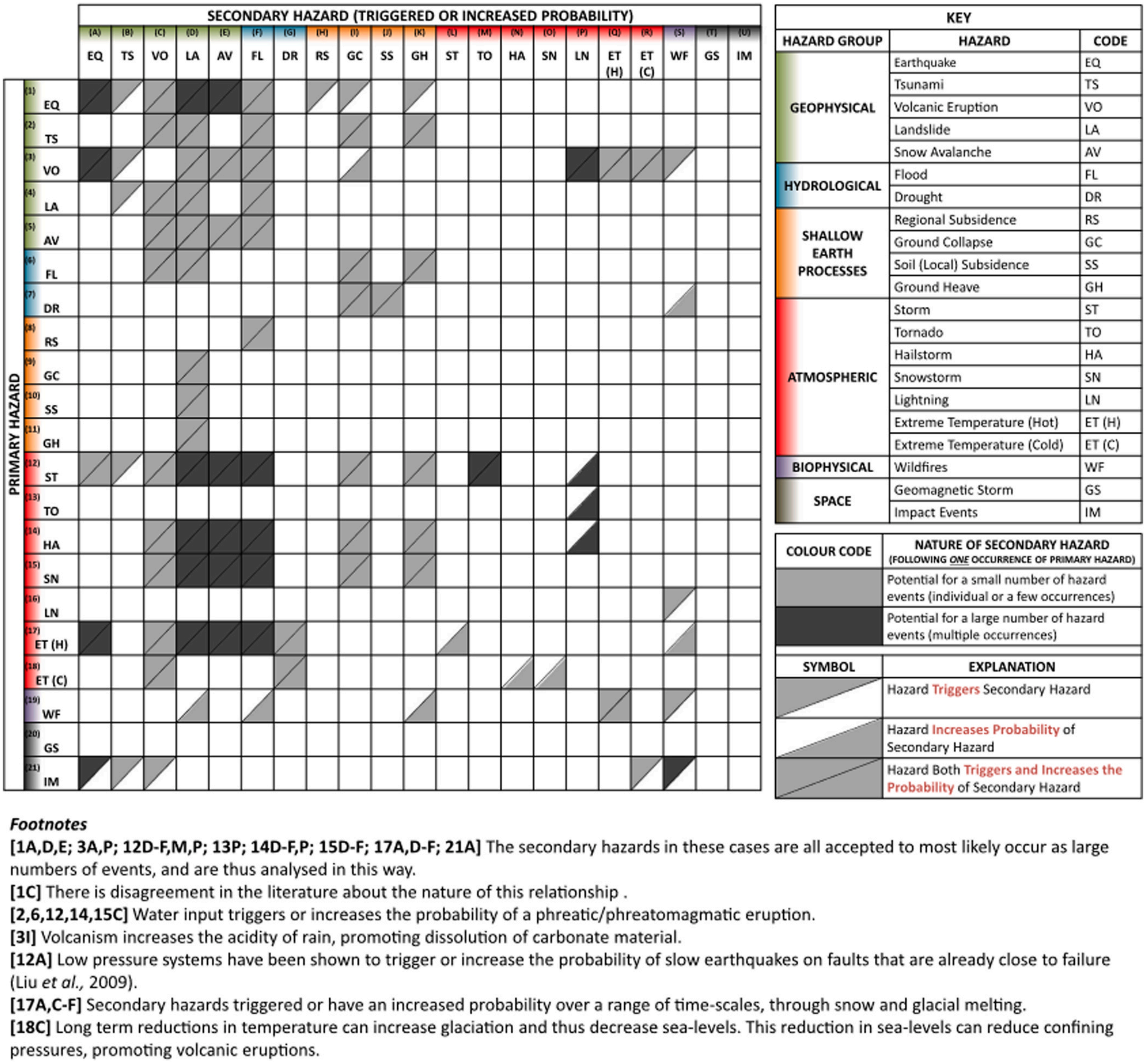
Data avail ability

No new data sets external to what is stated in this manuscript were generated or analyzed.

Annex 1. : Identification of hazard interactions. Source: Gill and Malamud (2014)



KEY		
HAZARD GROUP	HAZARD	CODE
GEOPHYSICAL	Earthquake	EQ
	Tsunami	TS
	Volcanic Eruption	VO
	Landslide	LA
	Snow Avalanche	AV
HYDROLOGICAL	Flood	FL
	Drought	DR
SHALLOW EARTH PROCESSES	Regional Subsidence	RS
	Ground Collapse	GC
	Soil (Local) Subsidence	SS
	Ground Heave	GH
ATMOSPHERIC	Storm	ST
	Tornado	TO
	Hailstorm	HA
	Snowstorm	SN
	Lightning	LN
	Extreme Temperature (Hot)	ET (H)
	Extreme Temperature (Cold)	ET (C)
BIOPHYSICAL	Wildfires	WF
SPACE	Geomagnetic Storm	GS
	Impact Events	IM

COLOUR CODE	NATURE OF SECONDARY HAZARD (FOLLOWING ONE OCCURRENCE OF PRIMARY HAZARD)
▒	Potential for a small number of hazard events (individual or a few occurrences)
■	Potential for a large number of hazard events (multiple occurrences)

SYMBOL	EXPLANATION
◩	Hazard Triggers Secondary Hazard
◪	Hazard Increases Probability of Secondary Hazard
▨	Hazard Both Triggers and Increases the Probability of Secondary Hazard

Footnotes

[1A,D,E; 3A,P; 12D-F,M,P; 13P; 14D-F,P; 15D-F; 17A,D-F; 21A] The secondary hazards in these cases are all accepted to most likely occur as large numbers of events, and are thus analysed in this way.

[1C] There is disagreement in the literature about the nature of this relationship .

[2,6,12,14,15C] Water input triggers or increases the probability of a phreatic/phreatomagmatic eruption.

[3I] Volcanism increases the acidity of rain, promoting dissolution of carbonate material.

[12A] Low pressure systems have been shown to trigger or increase the probability of slow earthquakes on faults that are already close to failure (Liu *et al.,* 2009).

[17A,C-F] Secondary hazards triggered or have an increased probability over a range of time-scales, through snow and glacial melting.

[18C] Long term reductions in temperature can increase glaciation and thus decrease sea-levels. This reduction in sea-levels can reduce confining pressures, promoting volcanic eruptions.

Annex 2. : Calculations concerning steps 7, 8, 9, and 10 of the ICI-MRD framework

2.1 Calculations to determine the items absolute weight (*IAW*).

$$IAW_{SE} = \sum_{k=1}^{4} MRI_{k;SE} = (7+5+3+8) = 23 \tag{3a}$$

$$IAW_{FS} = \sum_{k=1}^{4} MRI_{k;FS} = (1+1+2+1) = 5 \tag{3b}$$

$$IAW_{PE} = \sum_{k=1}^{4} MRI_{k;PE} = (2+1+2+2) = 7 \tag{3c}$$

$$IAW_{PW} = \sum_{k=1}^{4} MRI_{k;PW} = (2 + 1 + 7 + 3) = 13 \tag{3d}$$

$$IAW_{MC} = \sum_{k=1}^{4} MRI_{k;MC} = (2 + 2 + 1 + 1) = 6 \tag{3e}$$

$$IAW_{EE} = \sum_{k=1}^{4} MRI_{k;EE} = (5 + 1 + 3 + 3) = 12 \tag{3f}$$

$$IAW_{HS} = \sum_{k=1}^{4} MRI_{k;HS} = (4 + 5 + 1 + 1) = 11 \tag{3g}$$

$$IAW_{HS} = \sum_{k=1}^{4} MRI_{k;HS} = (2 + 2 + 4 + 9) = 17 \tag{3h}$$

2.2 Calculations to determine the items relative weight (*IRW*).

$$IRW_{SE} = \sum_{k=1}^{4} MRI_{k;SE} \times LPF_k = (7 \times 0.18) + (5 \times 0.14) + (3 \times 0.17) + (8 \times 0.04) = 2.79 \tag{4a}$$

$$IRW_{BWT} = \sum_{k=1}^{4} MRI_{k;BWT} \times LPF_k = (1 \times 0.18) + (1 \times 0.14) + (2 \times 0.17) + (1 \times 0.04) = 0.7 \tag{4b}$$

$$IRW_{PE} = \sum_{k=1}^{4} MRI_{k;PE} \times LPF_k = (2 \times 0.18) + (1 \times 0.14) + (2 \times 0.17) + (2 \times 0.04) = 0.92 \tag{4c}$$

$$IRW_{PW} = \sum_{k=1}^{4} MRI_{k;PW} \times LPF_k = (2 \times 0.18) + (1 \times 0.14) + (7 \times 0.17) + (3 \times 0.04) = 1.81 \tag{4d}$$

$$IRW_{MC} = \sum_{k=1}^{4} MRI_{k;MC} \times LPF_k = (2 \times 0.18) + (2 \times 0.14) + (1 \times 0.17) + (1 \times 0.04) = 0.85 \tag{4e}$$

$$IRW_{EE} = \sum_{k=1}^{4} MRI_{k;EE} \times LPF_k = (5 \times 0.18) + (1 \times 0.14) + (3 \times 0.17) + (3 \times 0.04) = 1.67 \tag{4f}$$

$$IRW_{HS} = \sum_{k=1}^{4} MRI_{k;HS} \times LPF_k = (4 \times 0.18) + (5 \times 0.14) + (1 \times 0.17) + (1 \times 0.04) = 1.63 \tag{4g}$$

$$IRW_{BWT} = \sum_{k=1}^{4} MRI_{k;BWT} \times LPF_k = (2 \times 0.18) + (2 \times 0.14) + (4 \times 0.17) + (7 \times 0.04) = 1.60 \tag{4h}$$

2.3 Calculations to determine the hazards absolute weight (*HAW*)

$$HAW_{LN} = \sum_{e=1}^{8} MRI_{LN;e} = 7 + 1 + 2 + 2 + 2 + 5 + 4 + 2 = 25 \tag{5a}$$

$$HAW_{ETh} = \sum_{e=1}^{8} MRI_{ETh;e} = 5 + 1 + 1 + 1 + 2 + 1 + 5 + 2 = 18 \tag{5b}$$

$$HAW_{ETc} = \sum_{e=1}^{8} MRI_{ETc;e} = 3 + 2 + 2 + 7 + 1 + 3 + 1 + 4 = 23 \tag{5c}$$

$$HAW_{FL} = \sum_{e=1}^{8} MRI_{FL;e} = 8 + 1 + 2 + 3 + 1 + 3 + 1 + 7 = 26 \tag{5d}$$

2.4: Calculations to determine the $IRW_{e\ max}$

$$IRW_{SE\ \max} = \sum_{k=1}^{4} MRI_{k;SE} \times LPF_{k^*} = (7{\times}3) + (5{\times}3.33) + (3{\times}4) + (8{\times}4) = 81.65 \tag{7a}$$

$$IRW_{BWT\ \max} = \sum_{k=1}^{4} MRI_{k;BWT} \times LPF_{k^*} = (1{\times}3) + (1{\times}3.33) + (2{\times}4) + (1{\times}4) = 18.33 \tag{7b}$$

$$IRW_{PE\ \max} = \sum_{k=1}^{4} MRI_{k;PE} \times LPF_{k^*} = (2\times3) + (1\times3.33) + (2\times4) + (2\times4) = 25.33 \tag{7c}$$

$$IRW_{PW\ \max} = \sum_{k=1}^{4} MRI_{k;PW} \times LPF_{k^*} = (2\times3) + (1\times3.33) + (7\times4) + (3\times4) = 49.33 \tag{7d}$$

$$IRW_{MC\ \max} = \sum_{k=1}^{4} MRI_{k;MC} \times LPF_{k^*} = (2\times3) + (2\times3.33) + (1\times4) + (1\times4) = 20.66 \tag{7e}$$

$$IRW_{EE\ \max} = \sum_{k=1}^{4} MRI_{k;EE} \times LPF_{k^*} = (5\times3) + (1\times3.33) + (3\times4) + (3\times4) = 42.33 \tag{7f}$$

$$IRW_{HS\ \max} = \sum_{k=1}^{4} MRI_{k;HS} \times LPF_{k^*} = (4\times3) + (5\times3.33) + (1\times4) + (1\times4) = 36.65 \tag{7g}$$

$$IRW_{BWT\ \max} = \sum_{k=1}^{4} MRI_{k;BWT} \times LPF_{k^*} = (2\times3) + (2\times3.33) + (4\times4) + (7\times4) = 56.66 \tag{7h}$$

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