Resilience-based framework for enhancing NaTech risk management in industrial critical infrastructures

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“Resilience-based framework for enhancing NaTech risk management in industrial critical infrastructures”

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Abstract

Industrial facilities, once considered isolated entities, are now approached as complex socio-technical systems that involve intricate networks operating within the confines of the surrounding environment. The increasing frequency of extreme natural events due to climate change has highlighted the vulnerability of industrial plants to NaTech (natural hazards triggering technological scenarios). Current methodologies for NaTech risk assessment focus predominantly on immediate consequences, overlooking the long-term complexities that both industrial systems and their surrounding territories may face. This research proposes a resilience-based framework for NaTech risk management, considering three main stages—awareness, preparedness, recovery—and a loop for continuous learning to address the evolving NaTech challenges. Awareness emphasizes proactive vulnerability characterization under the function-location perspective. It addresses the interactions between industrial plants and multi-hazard contexts by implementing innovative methodological procedures based on qualitative, quantitative, and spatial techniques. Preparedness is supported by an innovative multi-risk tool considering the dynamic vulnerability of equipment categories to individual and overlapped interacting hazards, able to deploy the vulnerability into hierarchical safety layers to design robust and context-specific safer systems. The recovery stage is described through a retrospective case of hydrocarbon pollution caused by rainfall, integrating countermeasures and sustainable technological solutions. Overall, this research highlights the need for multidimensional approaches to tackle the evolving challenges posed by NaTech events. The outcomes present a comprehensive resilience-based framework, and operational procedures guiding the practical implementation of resilience principles and advancing the understanding of complex industrial systems while supporting their long-term sustainability facing natural factors.

Keywords Critical infrastructures · NaTech · Multi-hazard · Process industry · Resilience · Vulnerability

1 Introduction

In the past, process facilities were perceived as isolated establishments to produce chemicals and other products. Conversely, these plants involve intricate networks of infrastructure, materials, operators, and organizations working under predetermined protocols, guidelines, or directives to provide essential services (Jain et al. 2017). These technological systems operate within the confines of geographical areas, where productive, social, cultural, and natural phenomena occur across time and space, thereby strengthening the connection between the industrial and territorial contexts (Pereno and Barbero 2020). Consequently, process plants are regarded as integral parts of interconnected socio-ecological and technological systems (SETSs), rather than standalone facilities. These systems should account not only for undesired technological outcomes at the site level, but also for those coming from the complex interplay between process plants and external factors, resulting in potential negative impacts on people, infrastructure, or the environment (Krausmann and Necci 2021).

Regarding these negative impacts, decision makers face a new challenge in high-impact and low-probability (HILP) scenarios, often overlooked in hazard assessments due to their low likelihood (Paltrinieri and Reniers 2017). These events are particularly complex since they are frequently the result of cascading and escalation events (Mesa-Gómez et al. 2020). One specific type of HILP is the so-called

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"NaTech event", where natural hazards trigger technological accidents involving the release of hazardous materials (Krausmann et al., 2017). The occurrence of NaTech events is increasing due to the rising frequency of extreme natural events in the context of climate change (Ricci et al. 2021), as well as the increasing susceptibility of industrial facilities due to the increase in complexity and the interconnection among them (Gao et al. 2023).

Over the past decades, various perspectives on NaTech risk management have been explored worldwide among academia and international organizations. For instance, Cruz and Okada (2008) proposed a methodology for the preliminary assessment of NaTech risks, assisting local governments and promoting safer urban environments. Additionally, natural factors such as floods (Cozzani et al. 2010), lightning (Castro Rodriguez et al. 2024; Renni et al. 2010), earthquakes (Krausmann et al. 2011), and extreme temperatures (Ricci et al. 2023a, b) have been studied using semi-quantitative techniques based on historical recorded data, while comprehensive studies of NaTech incidence with process industry were carried out on multiple natural factors (Gao et al. 2023; Ricci et al. 2021). In parallel, quantitative frameworks have been developed to estimate the risk of NaTech occurrences, focusing on dominant factors such as floods, seismic events, or lightning and their potential domino effects (Antonioni et al. 2007, 2015; Cozzani et al. 2014; Necci et al. 2016; Misuri et al. 2020). Additionally, some frameworks have provided specific fragility models for various industrial equipment, such as atmospheric storage tanks or horizontal vessels, exposed to single natural hazard effects (Salzano et al. 2003; Necci et al. 2014; Caratozzolo et al. 2022).

Recent efforts have been made to capture how concurrent hazards impact process facilities and lead to equipment failures, depending on their interdependence (Lan et al. 2021), highlighting how ignoring multiple hazards together can seriously underestimate risk (Bernier and Padgett 2019). Moreover, recent dynamic modeling frameworks account for the temporal evolution of triggering factors, their potential interactions with additional natural hazards, and their capacity to initiate domino effects within industrial clusters (Lan et al. 2022, 2024). Furthermore, Geographic Information Systems (GIS) have significantly improved the spatial modeling of multi-hazard threats and the land use implications in the environment surrounding the plant locations (Luo et al. 2022; Castro Rodriguez et al. 2025a). Emerging approaches have prompted a shift towards considering scenarios that were previously deemed unthinkable (Krausmann and Necci 2021; Necci and Krausmann 2022), while proposed rating systems-based frameworks have encouraged multi-stakeholder interactions aiming to certify the level of preparedness of industrial facilities with respect to NaTech risk (Pilone et al. 2021; Suarez-Paba and Cruz 2022).

Despite the efforts from the academy, most of the methods developed till now for the assessment of NaTech events address only the anticipation of immediate and short-term direct consequences of triggered technological scenarios (Valente et al. 2025). Nonetheless, the repercussions of these events can be distributed over time and space, enduring for an extended period, not only affecting the functionality of facilities to bounce back to desired performance but also stressing the socio-ecological processes in their surrounding contexts (Suarez-Paba et al. 2020).

Nowadays, NaTech accidents continue to occur, exposing weaknesses in the corporate systematic risk management strategies. This underscores the need to integrate novel insights developed in academia, apply multidisciplinary and crosscutting approaches, and enhance government oversight to address these challenges effectively (Hu et al. 2025). From the perspective of risk governance, while NaTech events are recognized to be challenging due to their multi-hazard and multi-stakeholder nature (Krausmann and Necci 2021), global regulatory authorities have generally provided limited attention to this issue. One good example is the Directive 2012/18/EU[1] (Seveso III) within the European context, where it is specified that establishments falling under its provisions must detail the description of major accident scenarios related to natural causes.

Indeed, some noteworthy major industrial accidents that occurred in Europe over the years indicate that the interplay between technological and natural hazards, although unlikely, may certainly cause a significant impact on infrastructures, people, and the environment (BARPI 2022; eMARS 2022). For example, the ethylene production plant Dutch State Mines in the Netherlands experienced a gas leak in 1975, resulting in a massive vapor cloud explosion, causing 14 fatalities and 107 injuries, with low-temperature embrittlement as the suggested cause. Additionally, in 1998, following a landslide, a break in a waste basin at a pyrite mine in Aznalcollar, Spain, resulted in the flow of acidic water and heavy metal-laden sludge into the Río Agrio and Guadiamar rivers. Over a 20-kilometer length, this spill stretched 200–300 m, endangering ecosystems. Thirty tons of fish were lost, along with tens of thousands of other species, and very high cleaning costs. Furthermore, in 2010, a rupture in the dikes of an aluminum plant in Kolontár, Hungary, caused by intense rain, led to a spill that contaminated rivers and ecosystems, resulting in evacuations, plant closures, and a state of emergency. This event resulted in 10 deaths, 286 injuries, and the destruction of 284 homes.

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

Moreover, in 2023, a digest tank in a facility near Yarnton, Oxfordshire, England, was struck by lightning, setting fire to biogas. While no fatalities or injuries were reported, the fire damaged three of the five tanks on the site, provoking losses not only from the economic-operational perspective but also producing emissions to the atmospheric environment.

Currently, the Seveso III Directive 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 Plan (European Commission 2021). To achieve the goal of minimizing losses in lives, livelihoods, and health, there is a necessity to align global and European policies incorporated after the Seveso III last update in 2012, such as the 2030 Agenda for Sustainable Development, the Sendai Framework for Disaster Risk Reduction, and the Climate Adaptation Strategy. This framework constitutes a step forward, aiming to be all-inclusive in terms of hazards and stakeholder involvement, emphasizing the importance of multi-hazard comprehensive studies, including natural and man-made disasters.

Although the Seveso III Directive acknowledges that natural hazards can trigger major accidents—primarily referencing earthquakes and floods—it provides no clear guidance on managing NaTech risks and overlooks other natural factors and their potential interactions (Yalçın and Gürün 2025). Non-Seveso facilities are not bound by Directive 2012/18/EU, leaving natural hazard considerations largely absent or ad hoc, even though NaTech interactions can still trigger major accidents (Castro Rodriguez et al. 2025b) or cause chronic environmental impacts (Castro Rodriguez et al. 2022a).

In this context, Directive (EU) 2022/2557[2] (CER Directive) has been released, establishing that Member States must identify critical entities that might be disrupted by a disaster, and make a national strategy by January 2026 to strengthen their resilience. This new directive requires the development of integrated risk assessment studies for the infrastructures, considering all relevant man-made and natural hazards that could lead to major accidents, in compliance with the applicable sector-specific European Union legislation (including Seveso III). The challenge for the upcoming implementation of Directive (EU) 2022/2557 lies in the fact that Seveso III offers limited guidance on resilience and vulnerability, maintaining a predominantly hazard-focused approach (Tannous et al. 2025).

To address all the issues discussed above, this research aims to develop a resilience-based framework to enhance NaTech risk management in industrial critical infrastructures through a holistic approach guided by operational procedures for the practical implementation of resilience principles tailored to the multi-risk nature of NaTech events. This framework comprises three main stages: awareness, preparedness, and recovery, accounting for the spatial-temporal NaTech multi-dimensionality. First, awareness emphasizes proactive vulnerability characterization under the function-location perspective. Second, preparedness is supported through an innovative multi-risk tool considering the dynamic vulnerability of equipment categories to individual and overlapped interacting hazards, which can deploy the detected vulnerability into hierarchical safety layers to design robust and context-specific safer systems retrofitting the infrastructure, strengthening the use of barriers, and developing effective emergency plans. Third, recovery considers immediate adaptation post-disruption and long-term restoration strategies to bounce back the system functionality after suffering a NaTech event. Finally, the integration of lessons constitutes a loop for continuous learning to address the evolving NaTech challenges. This framework aims not only to contribute to the understanding of complex industrial systems facing natural disruptions but also to support the long-term sustainability of critical entities that deliver essential services.

This article uses existing conceptual frameworks to position process plants as *industrial critical infrastructures* (ICI) that provide essential services and have the potential to cause NaTech accidents, regardless of whether they are under the Seveso Directive or not. These infrastructures match totally or partially with some categories under the CER Directive sectors, including energy, drinking water, wastewater, and the production and processing of food. Specifically, this research uses case studies belonging to the critical energy infrastructures sector.

After this introductory **Sect. 1**, this paper is organized as follows: The adopted theoretical foundations of resilience applied to the NaTech contexts are presented in **Sect. 2**. **Section 3** is the core of this research, where a resilience-based framework structured around three stages is described together with the articulated methodological procedures associated with each stage, and introduces the study cases. **Section 4** outlines the findings and insights after framework implementation. Finally, **Sect. 5** summarizes the main contributions and outlook for future implications.

2 Foundations of resilience in NaTech contexts

Resilience is widely recognized as a central concept in the adoption of holistic and safer perspectives for complex systems (Jain et al. 2017). It emerges from various processes occurring across different scales and involves factors such

[2] Directive of the European Parliament and of the Council on the resilience of critical entities and repealing Council Directive 2008/114/EC (European Commission, 2022).

as biophysical and socioeconomic characteristics, infrastructure, land use, the built environment, as well as external threats from climate and disasters (Hung et al. 2024). Owing to its interdisciplinary nature, resilience remains a broadly applied concept with diverse definitions and interpretations depending on the field and context (Hosseini et al. 2016).

Since its emergence in 2004, resilience engineering (RE) has been introduced in several industrial fields. Anticipation, monitoring, response, and learning were defined as the four major abilities of the systems (Hollnagel et al., 2006), in order to anticipate, withstand, and recover from the disruptions. Nonetheless, when focusing on the process industry, there is a recognized lack of clarity on the conceptual links between the resilience principles and practical procedures (Cincotta et al. 2019). Furthermore, focusing on disruptions caused by natural events, the several definitions of resilience used in process industry applications often remain too generic to address the unique characteristics of NaTech events (Valente et al. 2025).

To address this issue, Valente et al. (2025), after a systematic review, presented a resilience curve reporting the system performance tailored to the evolution of NaTech events in the chemical and process industry. The resilience evolution scenario described in **Fig. 1** outlines six phases of system performance, specifically addressing the unique characteristics of NaTech accidents. This approach not only considers the short-term consequences during the accident and its potential escalation effects but also examines the system behavior during the adaptation and recovery phases. This inclusion effectively incorporates the transition to long-term consequences into the analysis.

Although the generic resilience curve represents a notable effort to establish a consensus on the various phases of NaTech events throughout the resilience curve lifespan, it is evident in **Fig. 1** that the authors narrowly define the “resilience evolution process” with an arrow during the “disruptive performance period” — encompassing both the duration of the accident and the subsequent aftermath — (Castro Rodriguez et al. 2025a). In doing so, the key principles of resilience engineering are overlooked except for response: to effectively build resilience, it is crucial to engage in proactive measures that anticipate ongoing disruptions, in addition to responding during or after such events for survival or recovery.

Indeed, an inherent requirement of resilience is the constant pursuit of foresight to handle the changing nature of risk before harm occurs (Hollnagel et al., 2006). This proactive awareness is a dynamic process that forms the foundation for identifying, avoiding, or better preparing for future natural hazard challenges by focusing on managing the vulnerabilities during normal system performance (Hung et al. 2024). It consistently aligns with parts of the resilience concept used in research within the process industry domain (Chen et al. 2019; Katopodis and Sfetsos 2019; El-Halwagi et al. 2020; Krausmann and Necci 2021; Men et al. 2023).

Figure 1 provides just a resilience snapshot, limited to a single temporal dimension and often focused solely on metrics related to the overall chemical plant performance. However, this approach fails to account for the multidimensional nature of NaTech events, which must consider not only the plant integrity but also the dynamic location-based interplay of multiple natural factors and their cascading effects on various vulnerable elements. These elements include both internal components within the process plants as well as external entities such as utilities, transportation networks, environmental resources, and other interconnected infrastructure systems, as schematized in **Fig. 2**.

To address these challenges, **Table 1** provides a detailed characterization of the six phases of the NaTech accident resilience curve defined by Valente et al. (2025) and integrates the resilience engineering cycle based on the disruption profile model (Cottam et al. 2019), which is commonly

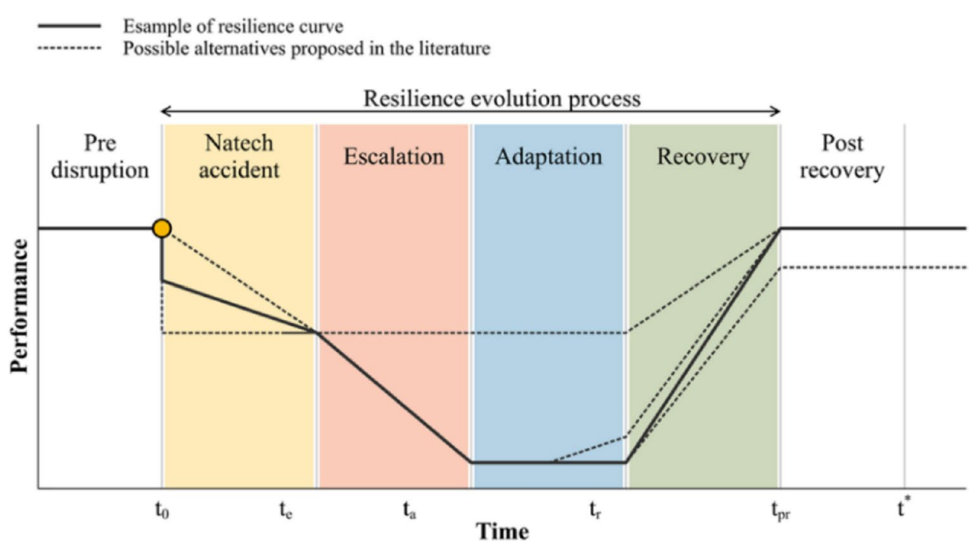

Fig. 1 Generic resilience curve for a NaTech accident, reporting system performance over time. The time frames are only indicative and do not have the intention to represent a proportion of the duration of the different phases. (t_0: time at which the natural hazard occurs; t_e: time at which escalation is triggered; t_a: time at which adaptation starts; t_r: time at which recovery starts; t_{pr}: time at which recovery ends; t^*: control time). *Source*: Valente et al. (2025)

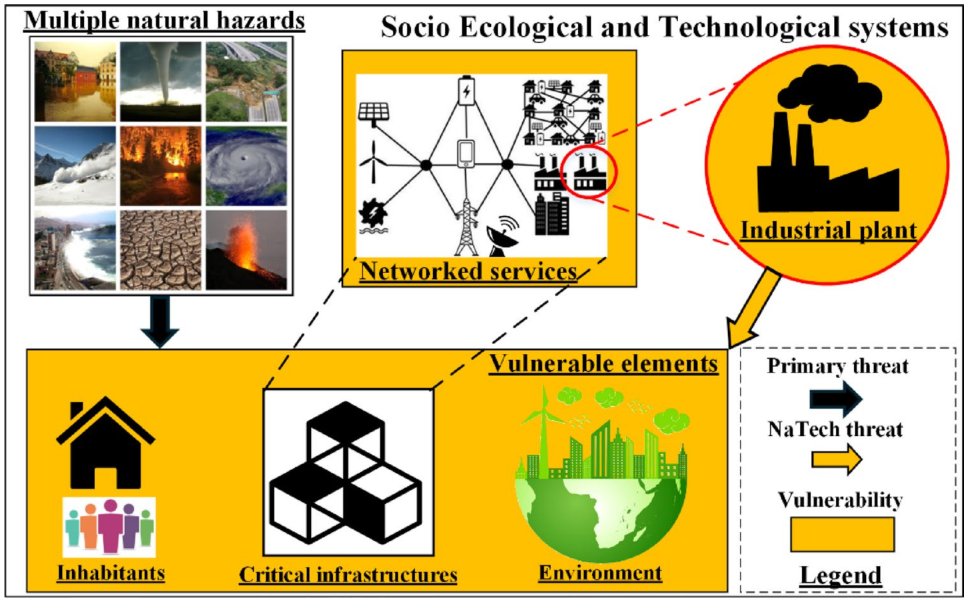

Fig. 2 Representation of the complex interplay among natural hazards, ICIs, and their interconnected surrounding context

Table 1 Comparison of disruption profile states with resilience curve phases for NaTech accidents

Disruption profile states	Performance (Target)	RE principle	Characterization of resilience curve phases for NaTech
Normal operations (pre-disruption)	Steady (avoidance)	Anticipate disruptions and monitoring signals	**Pre-disruption**: It refers to a state where the industrial plant operates at an expected level of performance. Even in the presence of hazards in its surroundings, the current robustness of the system absorbs these threats (Ratthaphong and Andrews 2021). Increasing awareness about the multiple hazards in the plant surroundings and the identification of vulnerable elements are crucial issues for enhancing the system's preparedness for future NaTech events.
Withstand the disruption (during disruption)	Decrease (absorb-resist)	Response (Short-term)	**NaTech Accident**: The NaTech event constitutes the principal cause of system performance decrease, which may occur instantly or gradually (Valente et al. 2025). It depends on various factors, such as the natural hazard initiator and its multi-hazard dynamics, the propagation pathway (direct or indirect), the infrastructure damaged state, and the ex-ante state of preparedness of the industrial system. However, industrial facilities are often unprepared for such events because of the lack of guidelines on how to apply contextualized countermeasures (El Hajj et al. 2015).
	Abrupt decrease (mitigate-resist)	Response (Short-term)	**Escalation**: The synergy of NaTech may result in a series of interconnected disruptive events (escalation) that may have worse results in the system performance (Zeng et al. 2023). These potential cascading scenarios could involve not only multiple vulnerable elements within the facilities but also those in their surroundings.
Recover from disruption impacts (post-disruption)	Steady (survive)	Response (transition between short and long-term)	**Adaptation**: When NaTech or its eventual escalation effects stop and the system reaches the point where the worst performance is achieved, operational strategies are introduced to adjust the already degraded state (Zeng et al. 2023). This can be considered the survivability point (Ratthaphong and Andrews 2021), in those cases in which the system did not completely lose its functionality. Performance may remain constant until the start of recovery activities, or it may eventually experiment with a short-term increment (Valente et al. 2025).
	Increase (recoverability)	Response (Long-term)	**Recovery**: This phase commences when actions are initiated to restore the chemical plant and its surrounding impacted elements to the desired performance level. The recovery speed is determined by a variety of factors, including the response times of proven effective restoration technologies (Castro Rodríguez et al., 2022b), as well as the specifics of each NaTech-triggered scenario. Furthermore, recovery speed is also influenced by the availability and planning of resources (Ratthaphong and Andrews 2021).
"New" normal operations	Steady (learning and avoidance)	Learning lessons and then starting again to anticipate disruptions, and monitoring signals	**Post-recovery**: This stage closes the resilience loop, constituting the "new normal" state after the modification achieved by the restoration methods and the introduction of lessons learnt. It can vary across a spectrum of potential outcomes depending on the level of resilience throughout the whole cycle. Thus, the new normal state could exhibit better, similar, or worse performance compared to before the disruption. The system may also completely lose its functionality in the absence of resilience (Castro Rodriguez et al. 2025a).

applied in the domain of critical infrastructures. Additionally, performance behaviors and corresponding system targets according to the RE pillars (Hollnagel et al., 2006) are aligned with each phase of NaTech evolution, reflecting the state of disruption of the system. This integrated information provides a systematic guide that enhances clarity, facilitates cross-referencing between resilience phases, disruption profiles, and performance targets.

An in-depth analysis of the information in **Table 1** highlights the need for a comprehensive resilience-based framework to enhance NaTech risk management, focusing on industrial critical infrastructures. This framework must go beyond merely addressing the immediate or long-term consequences of natural hazards impacting industrial critical infrastructures and their surroundings. Additionally, it should fully account for the multidimensional complexity of NaTech events, encompassing both normal and disruptive performance. Therefore, the anticipation of the spatial-temporal interplay between functional and territorial elements in multi-hazard contexts is a crucial issue.

3 Framework proposal

Putting together all the elements discussed above, a novel, holistic resilience-based framework is proposed in **Fig. 3** for enhancing NaTech risk management in industrial critical infrastructures.

This innovative framework combines risk and resilience approaches as parallel processes (Schauer et al. 2021) with

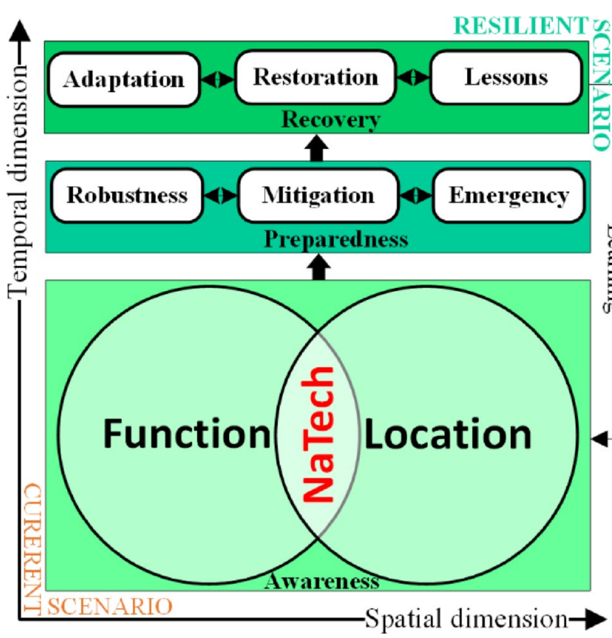

Fig. 3 Multidimensional resilience-based framework for enhancing NaTech risk management in ICIs (spatial-temporal axes are indicative rather than proportional)

the concept of territorial resilience (Brunetta et al. 2019), simultaneously addressing technological and territorial contexts through a function–location perspective. Then, the first attempt of this framework (Castro Rodriguez et al. 2022a) was applied based on 4 steps addressing the application of resilience engineering principles (Hollnagel et al., 2006) aligned with the cycle for a continuous improvement in preventing major accidents—prevention, preparation, response, and learning (European Commission 2024). Subsequently, these four steps were refined to the current three-stage framework—awareness, preparedness, and recovery—which align with the state evolution of the disruption profile—normal operations, withstand, and recover from NaTech events, respectively (Cottam et al. 2019). Finally, the bridge concept described in Poljanšek et al. (2017) was introduced, representing the transition from the "current" to a "resilient scenario". All the concepts addressed in this framework are aligned with the disaster risk reduction terminology (United Nations 2016).

Moreover, the framework in **Fig. 3** accounts for the multi-dimensional nature of NaTech, consisting of two spatial dimensions and three temporal stages. While the spatial dimensions do not intend to represent the real proportions of the physical area under analysis, they consider the bidirectional relationship between industries and territories outlined by Pilone et al. (2017). Similarly, the sequential stages—awareness, preparedness, and recovery—are just indicative of conceptual clusters aiming at the integration of operational procedures into an all-in-one resilience-based framework to enhance NaTech risk management. The originality lies in the precise articulation of these procedures within a holistic framework that connects vulnerability assessment with vulnerability-driven strategies, guiding the system to reach resilience consistently with the corresponding target in each NaTech phase (see **Table 1**).

3.1 Methods to enhance vulnerability awareness to multi-hazard

The "Awareness" is a proactive stage that takes into consideration the RE pillars of "anticipation and monitoring" (refer to **Table 1**) during the pre-disruption phase. It involves promptly identifying hidden signals to figure out the susceptibility of the system to be damaged punctually or gradually by natural events, tailoring the vulnerability definition given by the Intergovernmental Panel on Climate Change (2023). Methodological procedures based on qualitative, quantitative, and spatial techniques must be carried out to achieve proactive vulnerability characterization under the function-location perspective. This novel theoretical perspective conceptualizes the bidirectional relationship between ICIs and their multi-hazard territorial context as shown in **Fig. 4**.

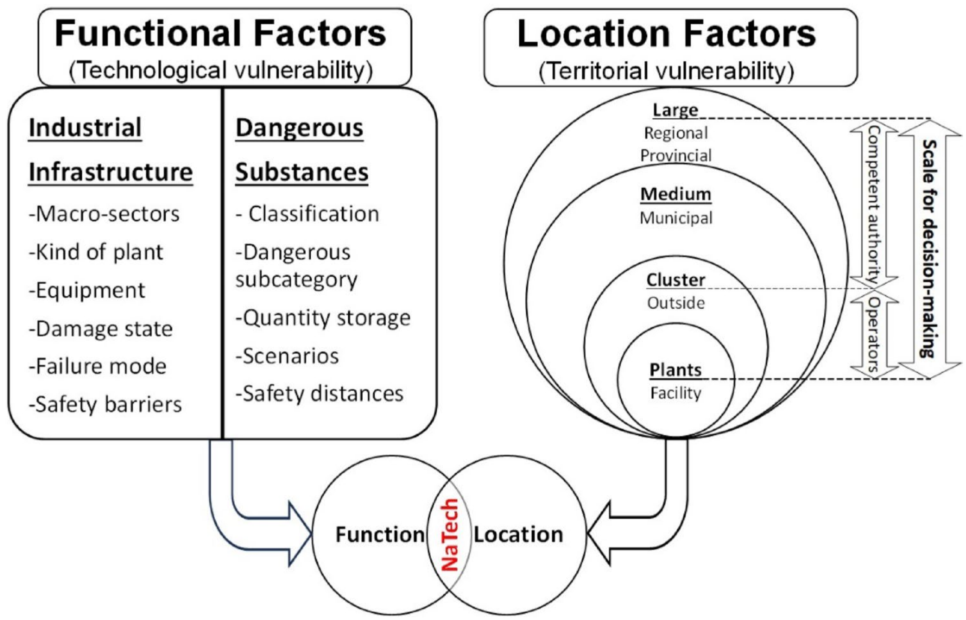

Fig. 4 Function-location approach to characterize NaTech vulnerabilities and support the decision-making process in industrial multi-hazards contexts. *Source*: Castro Rodriguez et al. (2025a)

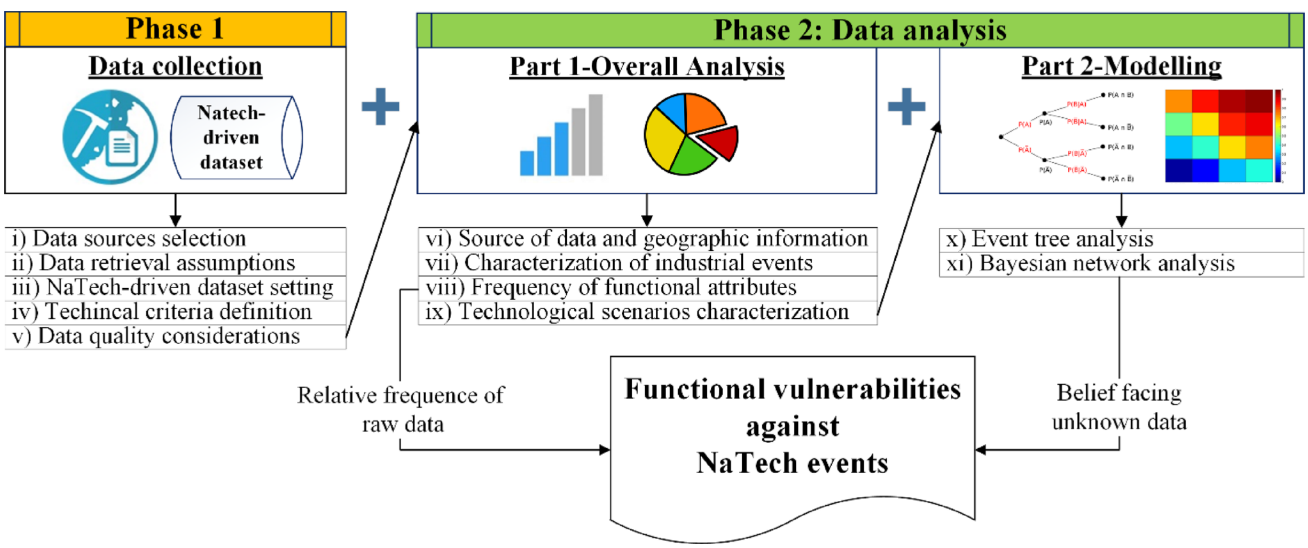

Fig. 5 Two-phase procedure to model functional vulnerabilities to NaTech in the process industry

On the left, the functional dimension reflects the technological vulnerabilities inherent to industrial attributes, subdivided into industrial infrastructure and dangerous substances. On the right, geophysical, socio-economic, and environmental factors capture the territorial predisposition both to threaten critical infrastructure and to be affected by technological scenarios. These territorial vulnerabilities are considered across different spatial scales, representing the interface where authorities, stakeholders, and practitioners engage with diverse decision-making levels and interests. The methodological steps to operationalize the function–location approach—and thus the awareness stage—are outlined in the following subsections.

3.1.1 Procedure to characterize functional vulnerabilities

Figure 5 illustrates the steps to characterize functional vulnerabilities. This procedure consists of two phases (data collection and data analysis) with eleven steps in total.

Phase 1 involves: **(i)** the source selection, **(ii)** the data retrieval assumptions, **(iii)** the NaTech-driven dataset setting, **(iv)** the technical criteria definition for the variables of interest, and finally **(v)** the data quality considerations. Phase 1 constitutes the cornerstone of the methodological procedure, and it is focused on data collection from open -source industrial accident databases, about historical records that happened within the process industry, caused directly or indirectly by the natural hazards of concern.

Moving to Phase 2, the data analysis is split into two parts. Phase 2–Part 1 is presented as an overall analysis, addressing qualitative and semiquantitative NaTech risk analysis. Part 1 addresses the records from diverse points of view, such as **vi)** source of data and geographic information, **vii)** characterization of industrial events, **viii)** determination of frequency for categories of functional attributes to the natural hazard of concern, and **ix)** technological scenarios characterization. On the other hand, Phase 2–Part 2 introduces modelling techniques in line with the quantitative risk assessment (QRA) techniques. For the sake of clarity, step **x)** stresses the logic pathways of the NaTech events through event tree analysis, while step **xi)** analyzes the hidden signals that denote conditional causality and frequency among the technological scenarios triggered, and their complex relationships with functional attributes within the dataset. It is important to note that this last step is open to any inclusion of quantitative risk assessment tools that improve data learning and uncertainty reduction.

3.1.2 Procedure to characterize the territorial vulnerability to multi-hazard

Similarly, a two-stage multi-scale spatial procedure is used to systematically characterize territorial vulnerabilities according to the location of concern. This procedure has 12 steps that downscale the territorial environment from a broad to a local scale. Spatially dependent analyses are conducted using open data and GIS, facilitating the identification of vulnerabilities to various hazards, advantageous to associated territorial susceptibilities with historical data, implementing the procedure in the previous **Sect. 3.1.1**. The outputs at each scale of interest yield a profile of territorial vulnerability, enhancing awareness across the various interests in the decision-making hierarchy. This approach provides flexibility to stop at the level of interest. Details about the steps for implementing this procedure can be found in previous research (Castro Rodriguez et al. 2025a).

3.2 Comprehensive multi-risk NaTech assessment supporting preparedness

Building on the “awareness” stage, a key question emerges: How can the vulnerabilities arising in the complex interplay between ICIs and their multi-hazard environments be leveraged to strengthen NaTech risk preparedness? System readiness should be pursued through the implementation of hierarchical safety layers, as proposed by Amyotte et al. (2018). Accordingly, the previously characterized vulnerabilities—analyzed from a function–location perspective—must guide the design of these safety layers, thereby supporting the ex-ante “preparedness” stage, which, during the disruption, targets “to absorb” or “to mitigate” the impacts of future natural challenges (see **Table 1**).

On the one hand, robustness—the degree to which a system or component can function correctly in the presence of invalid inputs or stressful environmental conditions (Specking et al. 2021)—should be achieved through primary prevention measures, such as implementing vulnerability-inherent designs or retrofitting the infrastructure (Amyotte and Khan 2021). These measures are “to absorb” the anticipated impacts of natural hazards effectively. On the other hand, whether the impacts of natural hazards overcome primary layers or might be amplified by cascading effects, then secondary layers must be introduced “to mitigate” disruptions, not only strengthening the use of safety barriers but also considering their potential degradation or malfunction during NaTech evolution (Misuri et al. 2020, 2023). Moving to the emergency plans, they are critical safety measures designed to mitigate disruptions. While emergency plans are duly implemented within the industry, it is acknowledged that NaTech scenarios often compromise the effectiveness of these traditional response models. For example, emergency responders face numerous challenges during NaTech events, including limited resource availability, communication breakdowns, equipment failures, extended response times, and the complexities of managing dual crises and their cascading effects (Ricci et al. 2024). These challenges underscore the urgent need for detailed, site-specific, and vulnerability-driven NaTech emergency response plans, along with guidelines for their design and testing, tailored to the specific characteristics of each system under consideration.

3.2.1 Critical infrastructure multi-risk deployment

To address the previous issues, the operationalization of the “preparedness” phase is supported by a novel adaptation of Quality Function Deployment (QFD) (Akao 1972). The innovative ICI-MRD (Industrial Critical Infrastructure–Multi-Risk Deployment) framework (**Fig. 6**) addresses theoretical formulations discussed in previous work (Castro Rodriguez et al. 2025c) to capture the function–location perspective and tailor the unique characteristics of multi-risk NaTech scenarios. Therefore, the ICI-MRD framework is fed by the outputs of the “awareness” stage (see **Sect. 3.1**) and comprehensively assesses the dynamic influence of multiple hazards inherent to the plant location on various standardized categories of industrial items, which may trigger technological scenarios. Details about how to implement the ICI-MRD framework in an energetic critical infrastructure are in Castro Rodriguez et al. (2025d).

Through this framework a punctual vulnerability multi-risk value (PIMRV) is determined (see step 10 in **Fig. 6**).

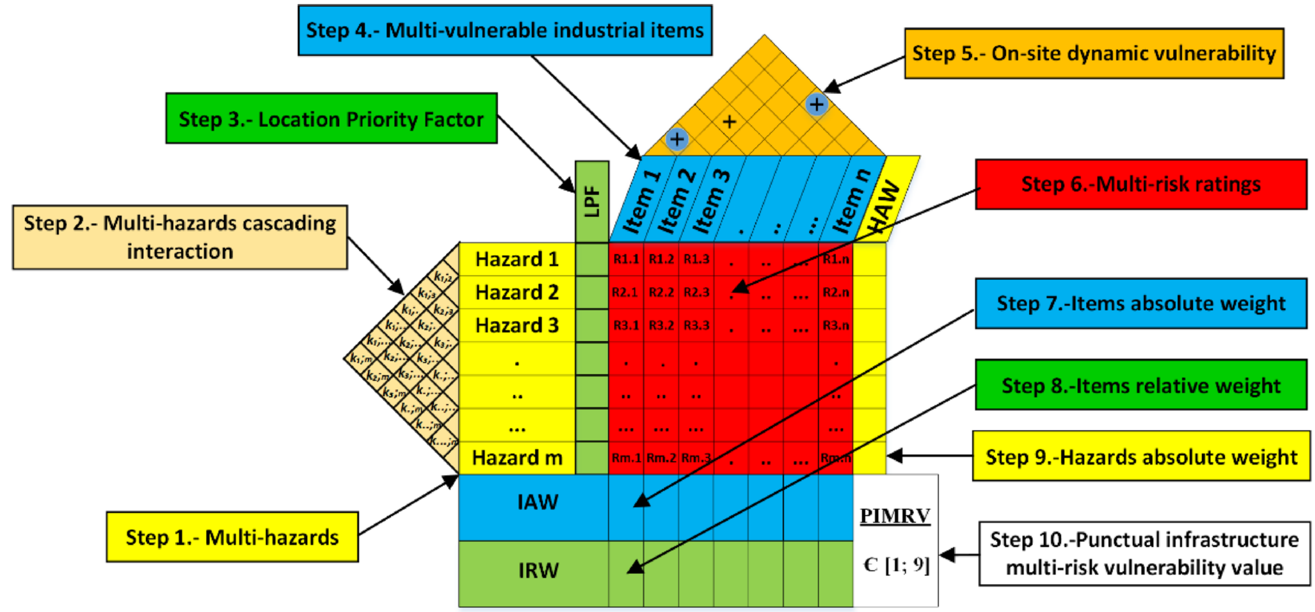

Fig. 6 Industrial Critical Infrastructure Multi-Risk Deployment (ICI-MRD) framework numbering the steps for its implementation. *Source*: Castro Rodriguez et al. (2025d)

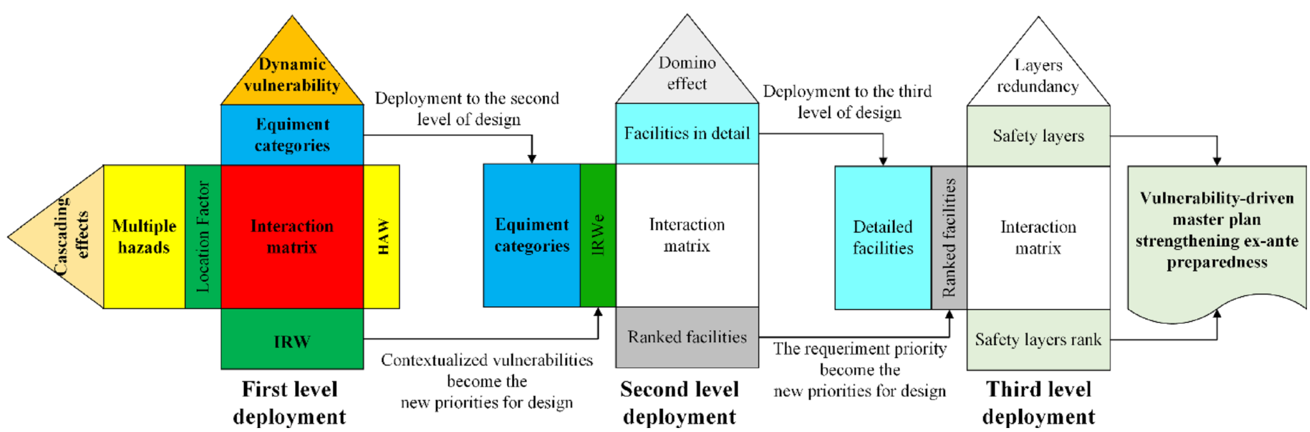

Fig. 7 Representation of the deployment process to an in-depth level of vulnerability-centered design. *Source*: modified from Castro Rodriguez et al. (2025d)

The PIMRV is associated with five categories of importance—Minor, Moderate, Strong, Critical, and Highly critical, ranging from broadly acceptable NaTech risk in the Minor priority category (where NaTech-focused fieldwork and routine inspections are appropriate), to intolerable risk in the Highly critical category (where regulatory measures should be enforced to restrict industrial activity at the given location). Moreover, ICI-MRD offers intermediate outputs valuable to develop strategies, based on the weights of contextualized hazards and items (steps 8 and 9 in **Fig. 6**). Building on these outputs, the iterative nature of the QFD tool allows for deeper analysis. For example, at the next level of deployment, the vulnerable elements (columns) represent the new requirements (rows) in a second-level matrix at a detailed operational scale, while the third level must deploy the vulnerability-driven insights into a layered master plan, strengthening short-term preparedness (**Fig. 7**).

For the design of a vulnerability-driven master plan to strengthen both on-site and off-site ex-ante preparedness, it is crucial to develop model-based simulations (PHAST, CFD) at a detailed operational scale, the integration of real-time data devices and advanced data analysis techniques to predict the dynamic interactions and progression of NaTech events and their consequences (Palacios et al. 2020; Papadaki et al. 2025; Rengel et al. 2018). Enhancing the effectiveness of short-term responses can reduce losses to human health, the environment, and infrastructures (Zheng et al. 2024).

3.2.2 Industrial accident potential from dangerous substances

While the framework introduced in **Sect. 3.2.1** focuses on function–location multi-risk interactions between infrastructure and territory, this is complemented by an index that evaluates the potential of process plants to trigger major industrial accidents involving hazardous substances. Developed in line with the legal requirements of European Regulation 2012/18/EU, the index extends its scope beyond major establishments to also include non-Seveso facilities. Drawing on the compliance index for each category of hazardous substance listed in Annex I of the Seveso III Directive, an innovative decision scale ranging from [0, 2) onwards was established. This scale introduces seven categories to classify the potential for major accidents based on the quantities of hazardous substances stored. More details are provided in Castro Rodriguez et al. (2025b).

3.2.3 Multi-dimensional comprehensive decision

Building on the previous sections, the comprehensive picture to characterize NaTech events is completed (see **Fig. 4**) by incorporating technological vulnerabilities contextualized to natural hazards according to site location, while also considering the hazardous substances stored in each plant, consistent with the definition provided by Krausmann et al. (2017).

On this basis, a decision matrix integrates the independent evaluations from **subsections 3.2.1** (Factor A) and **3.2.2** (Factor B) to support a comprehensive assessment of multi-risk NaTech potential, thereby addressing the question raised at the beginning of **Sect. 3.2**. The decision process relies on a categorical scale with four levels of risk tolerance: (i) broadly acceptable, (ii) specific measures should be introduced, (iii) major measures must be introduced, and (iv) intolerable NaTech risk. This scale is aligned with established criteria for decision matrices in NaTech research (Krausmann et al. 2011; Suarez-Paba and Cruz 2022).

3.3 Recovery

Although "recovery" is primarily conceived as a corrective stage following a NaTech disruption (see **Table 1**), certain elements of this stage must be addressed in advance to allow immediate intervention once the system reaches its survivability point (adaptation NaTech phase). The specific procedures will vary depending on the triggered NaTech scenarios but typically include damage assessment, primary debris, and contaminant cleanup, modifications to operating conditions, and restoration activities planning (Valente et al. 2025). These activities are premises to assist the system adaptation to its current degraded performance and start the transition to get back to a desired performance state in the long-term (see recovery stage in **Fig. 3**). Therefore, the restoration activities may be implemented immediately or with a delay, depending on how fast the system transits from the short-term to the long-term response.

Specifically, the speed and effectiveness of restoration activities depend on several factors connected to the specific characteristics of the NaTech-triggered scenarios. A rehabilitation project should be carried out according to the availability of critical resources. Typical activities include in-depth clean-up activities, maintenance, repair, and substitution of components and equipment, simplification of operational procedures for the reduction of human errors, optimization of technological operating conditions to stabilize operations, operational and environmental monitoring, implementation of rehabilitation technologies with proven effectiveness, and incorporation of sustainable tendencies.

Finally, the classical resilience engineering pillar of "learning" is incorporated through a feedback loop. This loop is embedded in the NaTech post-recovery phase (Valente et al. 2025), enhancing the system capacity for continuous improvement by leveraging lessons learned from its own experiences or similar historical events.

3.4 Introduction of case studies

The implementation of the resilience-based framework presented and articulated in the previous **Sect. 3.1**, **3.2**, and **3.3** is stressed through two complementary case studies. The two stages aimed at raising "awareness" and supporting the short-term "preparedness" were illustrated through an Italian case study involving a thermoelectric plant, classified as critical energy infrastructure in line with Directive (EU) 2022/2557. Moving to the "recovery" stage, the integration of long-term strategies into an all-in-one framework represents a novel approach. However, the post-disruption nature of recovery makes it challenging to provide a comprehensive case study that illustrates all stages at present. As an alternative, authors draw on a decade of studies conducted on critical energy infrastructures in Cienfuegos, Cuba, to illustrate the articulation of restoration actions and lessons learned that can be articulated in NaTech-impacted environments with similar industrial facilities. Specifically, the Cuban case focuses on scenarios triggered by the interaction of recurrent rainfall with critical components of industrial wastewater treatment systems in energy infrastructures, which have resulted in hydrocarbon pollution of the environment.

3.4.1 Case 1 (Italian)

As outlined before, the Italian case study consisted of a thermoelectric plant including auxiliary technical systems necessary for production and operation, such as compressed air, treated wastewater, steam production, and warehousing. Within all the processes and functions of the plant, the following items were identified: atmospheric storage tanks, tall structures such as chimneys and process columns and equipment, heat exchangers, complex systems of pipelines, complex electrical networks, water treatment components, and storage of raw materials. More details about the Italian case study can be found in Castro Rodriguez et al. (2025a, b, c).

3.4.2 Case 2 (Cuban)

Moving to the Cuban case, since the primary documents related to it are published in Spanish, an overall description is provided to place the case in context. In Cuba, the energy sector relies heavily on small-scale distributed power plants, which constitute over 50% of the electricity generation capacity in the country. These plants are strategically located near consumption sites and use fossil fuels to meet the energy demands of industrial and residential sectors (Llanes Cedeño 2017). However, life cycle analyses of distributed electricity generation in Cienfuegos revealed significant environmental and human health impacts that had previously received little attention (Rodríguez Pérez et al. 2014). Among these, hydrocarbon pollution of soil and water was identified as a major negative impact, degrading the environmental performance of distributed power generation (Medel-González et al. 2015).

Hydrocarbon pollution, frequently caused by daily operations such as fuel purification, equipment maintenance, water treatment, and storage tank upkeep, represents a persistent stressor for territories (Varjani et al. 2017). To address this issue, a territorial monitoring program was established, integrating data from industrial activities and their immediate environmental receptors as detailed in Castro Rodríguez et al. (2021). This program, focused on facilities across Cienfuegos, provided a snapshot of the industrial energy pollution in the region. Figure 8 illustrates the concentrations of total petroleum hydrocarbons (TPH) detected in the environment surrounding industrial facilities in Cienfuegos. The density and distribution of monitoring points highlight significant TPH contamination, especially in the bay area, where urban and economic activities converge.

This lagging indicator of environmental performance prompted environmental technological audits (Castro-Rodríguez et al., 2020), which identified key shortcomings. Among these were human errors and deficiencies in stormwater systems that allowed oily discharges into the environment during heavy rainfall events. For detailed insights into the shortcomings, refer to Castro Rodríguez et al. (2021). These findings are consistent with recent research emphasizing the significant role of human errors and inadequate application of advanced knowledge in NaTech occurrences (Hu et al. 2025).

4 Results and discussion

This section is divided into three subsections to outline the findings of the resilience framework implementation described in **Sect. 3**.

4.1 Enhancing vulnerability awareness to multi-hazard

Vulnerability awareness is achieved through the implementation of the two-stage methodological procedures described

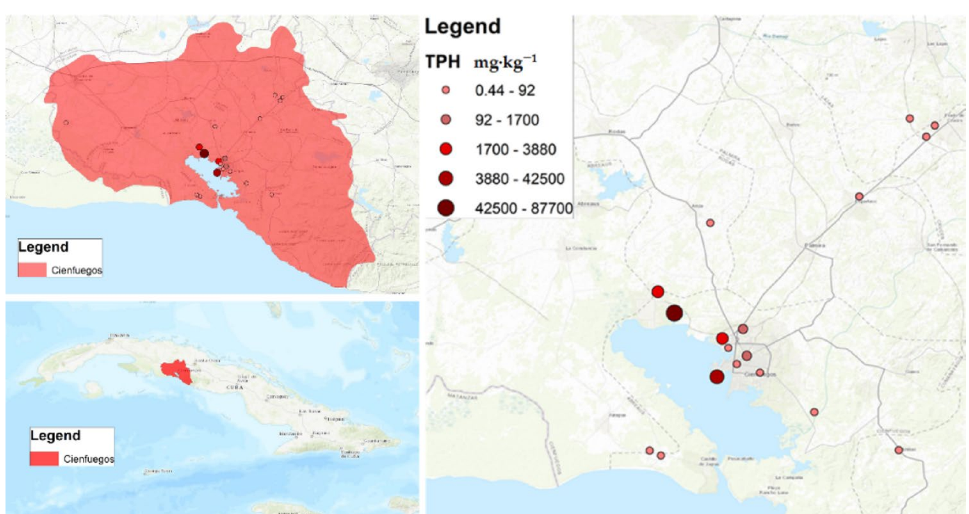

Fig. 8 Concentrations of TPH in the environment surrounding industrial facilities of Cienfuegos, Cuba. *Source*: Castro Rodriguez et al. (2022a)

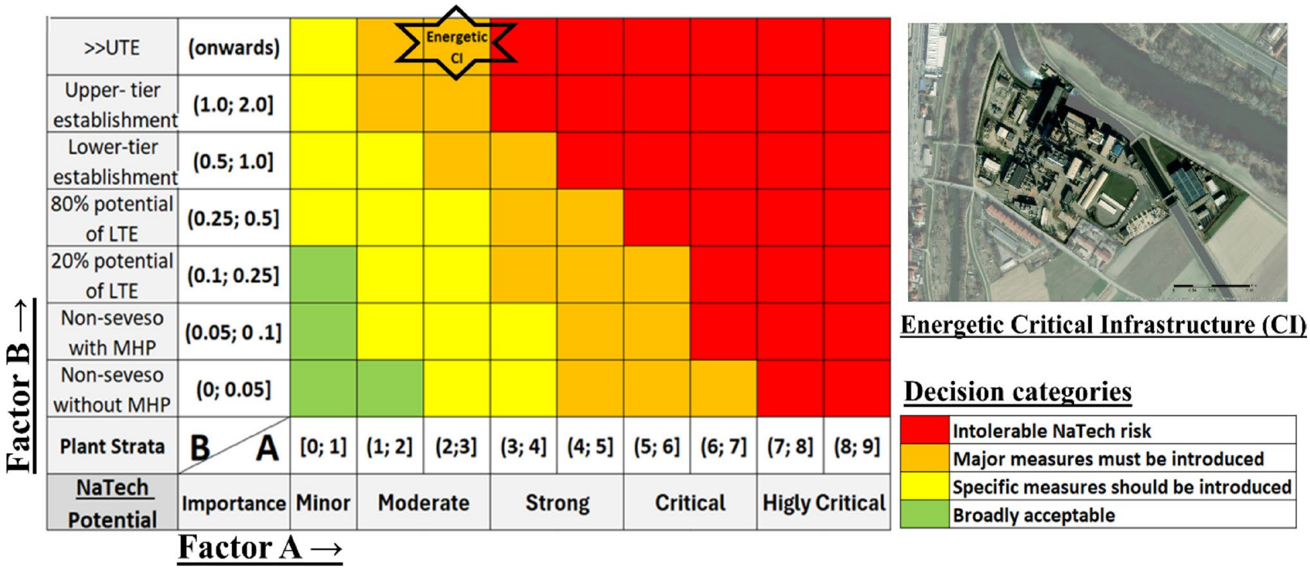

Fig. 9 Multi-risk NaTech decision matrix applied to the thermoelectric case study. (UTE: upper-tier establishment; LTE: lower-tier establishment; MHP: Major hazard potential = 5% of UTE)

in **subsections 3.1.1** and **3.1.2** under the function–location perspective. The procedure to characterize functional vulnerabilities (**subsection 3.1.1**) was implemented through the pilot case of lightning-triggered NaTech events in the process industry, since this phenomenon presents a critical trade-off between frequency (Ricci et al. 2021) and catastrophic consequences (Krausmann et al. 2011; Renni et al. 2010). The main result of the data collection (Phase-1) was a new dataset of 689 records, saved in a public repository (Castro Rodriguez et al. 2023), including records that span until 2022. Details about data analysis (Phase 2) can be found in previous work (Castro Rodriguez et al. 2024). This methodological procedure has been validated through similar studies applied even to non-natural factors (Vitale et al. 2026). On the other hand, in-depth discussion of the vulnerability profile contextualized at the industrial plant scale (thermoelectric) after implementing the two-stage multi-scale procedure to characterize the territorial vulnerability to multi-hazards (**subsection 3.1.2**) can be found in Castro Rodriguez et al. (2025a).

4.2 Supporting preparedness

Similarly, ex-ante preparedness is supported through the implementation of tools and indices in **subsections 3.1.2** and **3.2.2.** The validation of ICI-MRD framework (**subsection 3.2.1**) considered the influence of four natural hazards—lightning, extreme temperature hot, extreme temperature cold, and flooding on the eight equipment categories of a thermoelectric (Italian case study). The PIMRV ≈ 2.07 falls into "moderate" priority—closer to minor importance than to strong (Factor A). Deeper illustrations and insights discussion about the ICI-MRD implementation can be found in Castro Rodriguez et al. (2025d).

Based on the hazardous substances stored at the thermoelectric plant, their potential to cause a major accident was assessed (see **subsection 3.2.2**). No substances classified under the "health hazards" category were identified, and those belonging to the "physical hazards" category fall within the range of minor-risk facilities. However, Dense Fuel Oil (BTZ), classified under "environmental hazards," exceeds the upper-tier threshold for extremely critical establishments (obtaining a rate of 2 onwards). This result is consistent with the large quantities of combustible material stored at the plant for energy production. It also underscores the potential catastrophic consequences of a major accident, particularly due to the chronic toxicity and long-lasting effects on aquatic life. In-depth details in the calculation of the index of compliance, classification, and discussion about the dangerous substance potential to cause major accidents can be found in Castro Rodriguez et al. (2025b).

Figure 9 presents a decision matrix for a thermoelectric critical infrastructure, combining the independent inputs of PIMRV (horizontal Factor A) and the compliance index for dangerous substances with potential to cause major accidents (vertical Factor B), represented as (A; B) cells. The comprehensive multi-risk NaTech evaluation is thus based on the global acceptability determined by the location of each (A; B) cell within the matrix, which defines both the level of acceptability and the extent of strategies required—whether more infrastructural or operational (e.g., measures to manage hazardous substance inventories).

In particular, the analyzed case study shows an orange code (2.07; 2 onwards), indicating the need for strong measures. Here, the decision is primarily driven by the substance condition (Factor B input), which significantly exceeds the UTE threshold. Accordingly, priority should be given to managing and controlling the inventory of dangerous substances, identifying potential interactions among stored materials, and enhancing internal mitigation measures—such as reinforcing safety barriers and implementing redundant containment systems in case of spills.

4.3 Integration of long-term solutions (Recovery)

This section summarizes a retrospective analysis of restoration actions and lessons over a decade of studies on energy-critical entities in Cienfuegos, Cuba, to exemplify recovery from hydrocarbon pollution caused by technological interferences with rainfall.

Restoration efforts prioritized returning polluted areas to local communities for safe use according to the criteria of Ossai et al. (2020) and developing sustainable technologies to mitigate the periodic generation of oily sludge, preventing further harm to humans and ecosystems. A systemic approach, integrating industrial and territorial considerations, resulted in the implementation of over 400 measures across individual facilities. Key solutions included:

- Source reduction: Minimizing the generation of oily waste by reducing chemical inventories.
- Substitution: Replacing hazardous inputs in processes with less harmful alternatives.
- Process attenuation: Conducting operations under safer conditions to reduce risks.
- Simplification: Designing simpler processes to minimize human error.

Additionally, improved waste management practices, certification of disposal processes, and employee training were proposed to enhance overall performance. Examples of these restoration measures are detailed in Castro Rodriguez et al. (2022a). In parallel, a research project was undertaken to develop a bioremediation technique for treating hydrocarbon contamination (Castro Rodríguez et al., 2022b). This sustainable solution, even if it takes a long time based on the kinetics of degradation, has been demonstrated to be simpler and more effective than other alternatives. Its application aims to degrade hydrocarbons into oily sludges, which are generated periodically in industrial water treatment systems, stimulating the autochthonous microorganism and valorizing also other heterogeneous organic wastes from local industries. The different operating parameters and potentialities of the biopile ecotechnology developed can be consulted in Castro Rodríguez et al. (2022c) and Gutiérrez-Benítez et al. (2023).

The systematization of restoration measures addressing operational issues linked to interactions with meteorological factors yielded valuable lessons, which were standardized for stakeholders in the Cuban Electric Enterprise to enhance the performance of distributed power generation in Cienfuegos, Cuba. A key recommendation was the development of an in-situ bioremediation technique, specifically biopile ecotechnology, to manage oily sludges. These sludges cannot be avoided through management strategies nor disposed of in the environment due to their hazardous properties. Therefore, biopiles offer a sustainable and practical in-situ approach to addressing this environmental challenge at the plant scale, ensuring safer waste management within the essential service of electricity generation.

Despite the restoration measures discussed effectively supporting the long-term recovery of the system generation plants-territory, from hydrocarbon pollution caused by technological interference with rainfall, it is important to remark that this analysis is retrospective. If a resilient approach had been adopted earlier—proactively managing the environmental performance of these systems and analyzing the interplay between technological and natural factors critical to the location—the hydrocarbon pollution observed could have been largely prevented.

These results highlight that, to date, most studies have only addressed specific aspects or stages of resilience management. This underscores the need for a shift in mindset among operators, stakeholders, and practitioners to strengthen risk governance and management.

5 Conclusions and implications

NaTech events present unique challenges to the industrial critical infrastructures and their surrounding interconnected systems. However, current approaches are mainly focused on immediate, short-term consequences, neglecting their broader and longer-term impacts affecting facility functionality and stressing socio-ecological processes in their surrounding contexts. To address this gap, the latest academic progress associates the different phases of NaTech evolution with the trend of system performance fluctuations over time to enhance resilience.

This research introduces a comprehensive resilience-based framework to enhance NaTech risk management in industrial critical infrastructures. By integrating both established and innovative approaches, the framework accounts for system disruptions and performance behaviors, aligning system targets with the principles of resilience engineering across each phase of NaTech evolution. The framework focuses on three core stages—awareness, preparedness, and recovery—while incorporating a final feedback loop for continuous learning to address the dynamic challenges posed by NaTech events. Originality lies in the precise articulation of methodological procedures within a holistic resilience-based framework that connects vulnerability assessment with vulnerability-driven resilience strategies. Two case-studies on energetic critical infrastructures enable the validation of this novel framework. While the Italian case illustrated the proactive implementation of innovative procedures, the retrospective analysis of the Cuban case study highlighted the missed opportunities for preventive actions and withstanding NaTech disruptions. This underscores the necessity of embedding resilience principles into the early stages of risk management to avoid such scenarios in the future.

By addressing the multidimensional complexity of NaTech events and emphasizing the integration of resilience principles, this research provides a strong foundation for comprehensive NaTech risk management. The proposed framework not only enhances the resilience of industrial critical infrastructures but also targets to contribute to broader sustainable development goals, such as minimizing the environmental and societal impacts of industrial accidents and strengthening the adaptive capacity to climate-related hazards and natural disasters.

Further research is needed to translate the multi-risk NaTech potential into a detailed safety-layered master plan at the operational level, as outlined in Fig. 7. Achieving this requires model-based simulations, combined with the integration of real-time monitoring devices and advanced data analysis techniques. Together, these elements form the cornerstone for predicting the dynamic interactions, progression, and consequences of NaTech events.

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Declarations

Competing interests The authors declare no competing interests.

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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