




Definition of a simplified risk assessment methodology for NaTech scenarios triggered by tornado

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A B S T R A C T

Natural catastrophic events affecting technological systems may lead to the release of hazardous materials, giving rise to so-called "NaTech" events. The increasing number of NaTech events observed over recent years, possibly related to climate change, has reinforced interest in and the need to investigate the risk of exposure to natural hazards affecting the process industry. In the literature, most attention has been devoted to accidents triggered by floods and earthquakes, whereas no specific analysis protocols aimed at assessing the risk posed by tornadoes and severe wind gusts on production facilities are currently available. Consequently, the objective of this paper is to fill a gap in NaTech risk assessment by proposing a qualitative methodology for assessing the risk related to tornadoes and severe wind gusts. The proposed approach provides a basis for an objective, although simplified, comparison of both the risk posed by different plants potentially exposed to extreme wind events and the identification of the most critical equipment within a single plant. The analysis, partly based on existing qualitative methods, requires limited resources and data and relies on index-based evaluations.

A screening phase is first carried out by assessing the statistical incidence of the natural event using a European database, followed by the application of a qualitative method for evaluating equipment vulnerability and the consequences of their failure. Although the methodology was initially developed using data from the Italian territory, it can be applied to other countries, as demonstrated by the location sensitivity analysis performed at the end of the case study. The application of the methodology to a real case study showed that vertically developed and exposed assets, such as flare stacks, process columns, and gasoline storage tanks, represent the most critical equipment, consistently associated with medium to high risk levels. The sensitivity analysis, performed by relocating the same plant into different geographical areas, confirmed the robustness of the approach, as highly vulnerable assets remained critical across all locations, while less vulnerable equipment (e.g., pumps and phase separators) exhibited risk levels strongly dependent on local wind hazard conditions. These results demonstrate the capability of the methodology to effectively discriminate among territorial risk levels and to support the identification of installations requiring more detailed quantitative analyses.

1. Introduction

Natural catastrophic events represent a critical issue not only because of their direct effects on people and structures, but also due to their impact on industrial plants, potentially causing accidental releases of hazardous materials from installations and storage systems (Young et al., 2004). Cascading events that occur when technological systems are affected by the impact of natural hazards, which in turn trigger the release of energy or hazardous materials, are referred to as "NaTech" events, indicating their dual composition, natural and technological (Showalter and Myers, 1994).

These are events that differ from conventional "technological events" in terms of their initiating cause. While the latter are industrial accidents caused by internal factors such as malfunctions, design errors, and human operational errors, in NaTech events the initiating event originates outside the facility and is represented by a natural phenomenon, such as earthquakes, floods, or tornadoes. Therefore, in NaTech events,

the impact of a natural hazard on an industrial plant can be interpreted as an additional precursor event (i.e., a "basic event" in Fault Tree Analysis), whose frequency contributes to that of other possible initiating causes and whose origin is internal to the plant. This may result in an increase in both the frequency and severity of the accident scenarios associated with the release of hazardous substances (Antonioni et al., 2009).

In 2023, the Emergency Events Database (EM-DAT) recorded a total of 393 disasters related to natural hazards worldwide, resulting in more than 80,000 fatalities and economic losses exceeding 200 billion US dollars, both values significantly higher than the averages observed in the previous 20 years (Centre for Research on the Epidemiology of Disasters, 2024). Floods and storms together account for the majority of the total events recorded, with an incidence ranging from 70 to 80 % depending on the report considered (Centre for Research on the Epidemiology of Disasters (Centre for Research on the Epidemiology of Disasters, 2024)(CRED), 2024; Tin et al., 2024). Although less frequent,

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earthquakes represent the natural hazard with the higher impact on the population, due to their unpredictability and the vast areas often affected (Centre for Research on the Epidemiology of Disasters, 2024). Other authors have reported a substantial constancy in the number of natural disasters occurred yearly in the last two decades (Tin et al., 2024). Although some studies have hypothesized, investigated, and found a connection between climate change and increased frequency of extreme natural events and/or the intensity of their impact on the population (Hoegh-Guldberg et al., 2018; UNDRR, 2020) others remain more cautious in associating human activity and global warming with a truly central role in the intensification of these events (Visser et al., 2012)

Despite the difficulty in highlighting an unequivocal growth trend in the number of natural disasters over the years and in establishing a direct link with climate change, an increasing number of NaTech events can be observed (Ricci et al., 2021), especially if referred to storm-related accident (Necci et al., 2018). Although this trend may be influenced by multiple factors, such as the increase in the number of operating industrial sites or improved reporting practices in accident databases, it nevertheless confirms the relevance of NaTech hazards.

The evidence from these studies reinforces the interest and need to investigate the risk of exposure to natural hazards, whose consequences may affect workers, surrounding population, the environment, and critical infrastructure.

Necci and Krausmann (2022) identified five key elements characterizing NaTech risk: the capability of natural hazards to affect large geographical areas and multiple industrial sites simultaneously; their potential to trigger cascading effects, either generating secondary natural hazards or expanding the impact zone of an accident (e.g., dispersion of hazardous substances in floodwaters); their ability to compromise auxiliary systems and utilities (such as power supply, water, and communication lines), leading to loss of process control; the possible damage or destruction of engineered safety barriers; and the reduced effectiveness or inapplicability of standard emergency response measures commonly adopted for conventional technological accidents, such as shelter in place or evacuation.

In recent years, increasing attention has been devoted to NaTech-related issues. Several studies have analyzed past environmental disasters (Centre for Research on the Epidemiology of Disasters, 2024) UNDRR, 2020; Visser et al., 2012) focusing on the number of NaTech accidents that occurred as a consequences (Luo et al., 2020; Necci et al., 2018; Rasmussen, 1995; Renni et al., 2010; Showalter and Myers, 1994; Steinberg and Cruz, 2004). In particular, the work of Ricci et al. (2021) provides a systematic review of natural disasters and NaTech events of the last seventy years, reporting the frequency of direct and indirect releases of dangerous substances associated with these scenarios.

Among the possible natural events initiating industrial disasters, most of the attention in previous studies has been devoted to accidents triggered by floods and earthquakes (Antonioni et al., 2007; Busini et al., 2011; El Hajj et al., 2015; Krausmann and Mushtaq, 2008; Marzo et al., 2012). However, these hazards are not the only contributors to recorded NaTech events. According to Necci et al. (2018) and Ricci et al. (2021) the most frequent causes of NaTech events are associated with extreme meteorological phenomena, including flooding, lightning, and strong winds (Lara Carvajal et al., 2022). Indeed, some of the most emblematic NaTech events were triggered by storm phenomena, such as Hurricane Katrina and Hurricane Rita in 2005 (Griggs et al., 2017; Ruckart et al., 2008; Santella et al., 2010). Historically, Europe has also experienced severe storm events, such as Storm Xynthia in 2010 (Chadenas et al., 2014) and the 1953 storm surge in the southern North Sea (Wadey et al., 2015). Nevertheless, the interaction between extreme wind events and industrial plants remains comparatively under-investigated. Only a limited number of studies have explored the effects of extreme winds on specific industrial assets (Chen et al., 2024; Huang et al., 2022; Kameshwar, 2023; Santamato and Busini, 2025).

Storms may severely compromise the integrity of industrial plants

through various mechanisms. In process industries, asset damage may result from heavy rainfall, storm surges, and lightning strikes (Necci et al., 2018). In addition, wind action can directly stress buildings and other structures, with loads exceeding their design limits, as well as cause indirect damage through the impact of windborne debris, which may behave as projectiles (TRAS 320, 2015).

The most powerful tool to evaluate the impact of a natural event on industrial facilities is an extension of the classical Quantitative Risk Analysis (QRA) in which the natural event is considered as an additional cause triggering the incidental scenario. Specific procedures for the quantitative assessment of NaTech risk related to earthquakes and floods have been developed using QRA methods and can be found in Antonioni et al. (2009, 2007); Campedel et al. (2008); Fabbrocino et al. (2005). However, a limitation of QRA is that it requires many resources in terms of time and expertise, hence the need for short-cut methodologies that allow a more simplified analysis, taking into account the most relevant aspects of NaTech events, as well as describing them through easily accessible data, primarily for screening purposes, i.e., to identify situations in which a full QRA is warranted (Marzo et al., 2015).

Several qualitative or semi-quantitative methods for the assessment of flood- and earthquake-related NaTech risk have been proposed in the literature (Busini et al., 2011; Castro Rodriguez et al., 2023; Cruz and Okada, 2008; Galderisi et al., 2008; Krausmann and Mushtaq, 2008; Marzo et al., 2012, 2015; Novelli et al., 2024; Salzano et al., 2013). The outcomes of these approaches range from qualitative intensity scales, indicating the type and severity of potential releases, to aggregated performance indices that account for hazard characteristics, plant vulnerability, exposed population, and affected territory.

From a meteorological perspective, Tornadoes belong to the broader category of storms, together with cyclones (referred to by various terms such as hurricanes or typhoons depending on the geographical area) (NOAA, 2023), definable as “a set of extreme weather conditions characterized by very strong wind, heavy rain and often accompanied by thunder and lightning” (Cambridge dictionary).

However, despite falling within the same weather classification, tornadoes and hurricanes differ significantly in terms of genesis, intensity of precipitation and wind gusts, duration, and spatial extent (Clements and Casani, 2016). Consequently, their classification follows two different scales: hurricanes are classified according to the Saffir–Simpson scale (Meaden et al., 2007), whereas for tornadoes, several scales of intensity have been developed over time, such as the TORRO scale or the Fujita scale (Dotzek, 2009). The original Fujita scale was revised in 2007 and replaced by the Enhanced Fujita (EF) scale, which estimates tornado intensity based on observed damage indicators and classifies events into six categories, from EF0 to EF5 (Edwards et al., 2010), as reported in Table S1 of the Supplementary Materials. The Enhanced Fujita scale will be adopted in the present work.

The purpose of this paper is to address a gap in NaTech risk assessment by proposing a qualitative screening methodology for assessing NaTech risk associated with tornadoes and severe wind gusts, since just one qualitative methodology has been reported in the literature (Santamato and Busini, 2025).

The proposed methodology is the result of a collaborative effort between academia and industry and aims to provide risk analysts with a practical and rapid tool for the objective comparison of risk levels among different plants exposed to extreme wind events, as well as for the identification of the most critical equipment within a single facility. By enabling a preliminary assessment, the methodology supports the identification of installations requiring a more detailed QRA, thereby optimizing analytical resources and improving emergency preparedness. The approach relies on wind-related data, typically available from regional databases, and basic plant information, such as layout, equipment characteristics, and material properties.

Index-based approaches are widely adopted in the literature for the qualitative assessment of Natech risk, particularly for earthquake- and flood-related scenarios. However, most existing methodologies rely on

consolidated territorial zonation schemes and on pre-defined vulnerability frameworks. In the case of tornado-related Natech events, such foundational elements are largely missing. As a result, the proposed methodology required, as a first step, the development of an ad hoc territorial risk classification system, applicable to both Italian and non-Italian contexts, based on the systematic analysis of historical tornado events. Subsequently, a dedicated qualitative methodology was developed to assess the vulnerability of different types of industrial equipment. Although the input data required for the vulnerability assessment are comparable to those typically used in flood- and earthquake-related Natech analyses, the proposed approach leads to a different type of output. Individual indices are not recombined to derive a single overall risk class for the plant. The objective is not to assign a unique global risk level to the installation, but rather to perform an asset-oriented screening. Each asset is assigned a risk classification (low, medium, or high) based on the subdivision of a screening score obtained from three distinct indices accounting for geographical exposure, asset vulnerability, and potential loss-of-containment severity. This asset-level perspective allows a more targeted identification of critical elements and supports prioritization of mitigation actions in the absence of robust quantitative data.

Finally, the methodology is applied to a case study facility, followed by a sensitivity analysis considering the same plant located in five different geographical areas, demonstrating its capability to discriminate among different territorial risk conditions.

2. Materials and methods

This section presents the proposed NaTech risk assessment methodology, describing all its steps. Then, in the Results section, the

methodology is subsequently applied to a case study involving an Italian chemical facility, together with a sensitivity analysis with respect to plant location (including sites outside Italy).

The starting point is the definition of a methodological framework for the risk assessment. The analysis is divided into three main steps, as schematically illustrated in Fig. 1, where the first column, on the left, reports the input data and tools required for the analysis.

- Step 1 aims to determine the site-specific NaTech risk of the industrial facility as a function of its geographical location;
- Step 2 focuses on the assessment of the risk level associated with each item of equipment in the plant, based on its vulnerability characteristics and on the severity of the consequences resulting from potential damage and loss of containment, with reference to safety, environmental impact, and plant operability;
- Step 3, briefly outlined here, consists of the quantitative risk analysis (QRA), which lies beyond the scope of the present work.

2.1. Definition of a site-specific NaTech risk index

The first step of the methodology consists of a territorial screening aimed at assessing the predisposition of an industrial facility to be affected by tornadoes and strong wind gusts, depending on its geographical location. Italy was selected as the reference territory for the development of the methodology, as historical analyses show that several areas are exposed to intense wind phenomena.

Unlike earthquakes and floods, for which territorial zonation maps are available, no updated zonation dividing Italy into iso-risk areas for tornadoes currently exists. Although statistical analyses of tornado

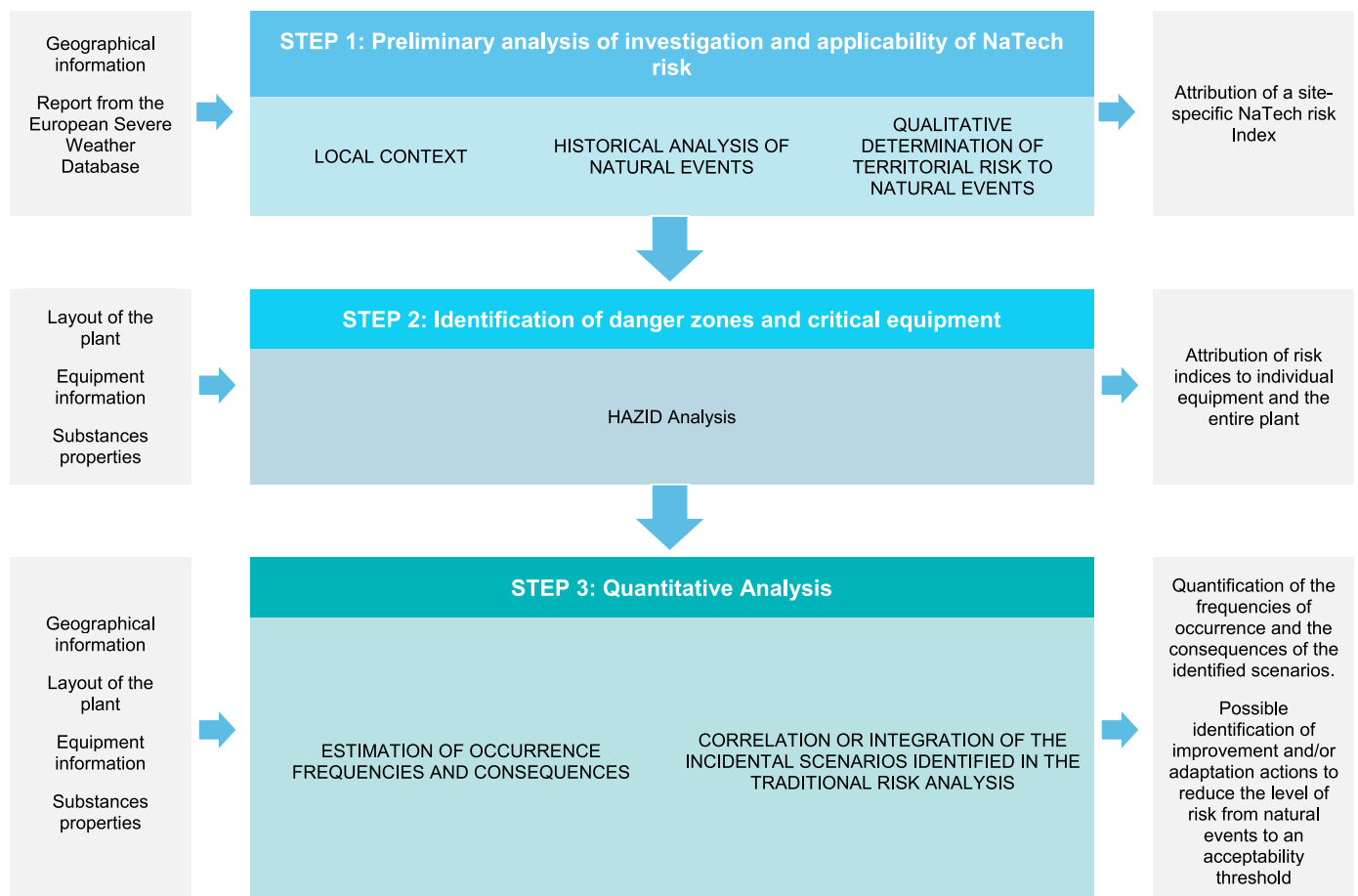


Fig. 1. Diagram of the proposed methodological flow for the NaTech risk assessment.

impacts have been carried out for specific time windows (from 1991 to 2000 (Giaiotti et al., 2007) and from 2007 to 2016 (Miglietta and Matsangouras, 2018)), these studies do not provide a comprehensive territorial risk classification. Therefore, a historical analysis was required to obtain the data necessary for the screening phase.

As a database, the European Severe Weather Database (ESWD) was chosen, since it appears to be the most suitable for analysis on the Italian territory and guarantees the generality (Groenemeijer and Kühne, 2014). The ESWD (ESWD, 2023) provides an extensive historical archive of severe weather events and uses an interactive map of the European territory with the possibility to set different search criteria, including investigation period, event type, place of occurrence (over land and/or over water) and report reliability level.

The database also enables spatial filtering by latitude and longitude, allowing the definition of rectangular survey areas. Accordingly, the Italian territory was divided into rectangular cells defined by geographical meridians (7°–19° E) and parallels (36°–47° N), resulting in 58 cells (Fig. 2a). Once the coordinates of the investigated site are known, the corresponding cell can be identified and used for the extraction of historical events. If the site is located close to the boundary between two or more cells, the analysis should be extended to adjacent cells, and the extracted events proportionally weighted. The criteria adopted for the historic analysis are reported in Table S2 of the Supplementary Materials.

By overlapping the morphological map of Italy (De Agostino and Claps, 2009) with the spatial distribution of tornado events extracted from the ESWD (1970–present, reliability levels QC1 and QC2), a clear correlation emerges between orography and wind-related events. As shown in Fig. 2b, tornadoes are mainly concentrated along coastal areas and in the Po Valley (blue areas), whereas significantly fewer events are recorded in hilly regions (green areas) and almost none in mountainous areas (orange and red zones).

After selecting “tornado” and “strong wind gusts” as the phenomena

of interest, the extracted events are classified according to their intensity. Tornado events are typically accompanied by an Enhanced Fujita (EF) scale classification in the database reports. Events classified as “strong wind gusts”, for which no funnel cloud formation is confirmed, are also considered in the analysis. To maintain a conservative approach, these events are assigned to a virtual class denoted as “<EF0”. However, when the event description includes indications such as “possible tornado formation”, a high number of injuries, or wind speeds exceeding 100 km/h, the event may conservatively be treated as equivalent to, and classified as, an EF0 tornado.

To account for both the frequency and intensity of events, a qualitative Frequency Index (FI) and Intensity Index (II) are assigned according to the criteria reported in Tables S3 and S4 of the Supplementary Materials.

Once all events are classified and the frequency indices for each intensity class are determined, a Screening Score (SS) is computed for each site to represent its territorial, site-specific NaTech risk. Starting from the definition of risk as the product of frequency and magnitude, the Screening Score is calculated as the sum of the products of the frequency and intensity indices for each class:

$$SCREENING\ SCORE = \sum FI_{class\ EF_n} \cdot II_{class\ EF_n} \quad (1)$$

Where n identifies the tornado intensity category according to the Enhanced Fujita scale.

Based on the Screening Score, the site is assigned to one of five Geographical Risk Levels, ranging from negligible to severe. The maximum theoretical score (63) corresponds to a territory experiencing, on average, more than 0.5 events per year for each EF category. The subdivision into five risk levels is obtained by assuming, for each level, the maximum frequency of occurrence only for a given intensity class and all lower classes, while neglecting higher-intensity events, as deeply explained and shown in Table S5 of the Supplementary Materials.

The five levels are defined as follows and enclosed in a matrix of

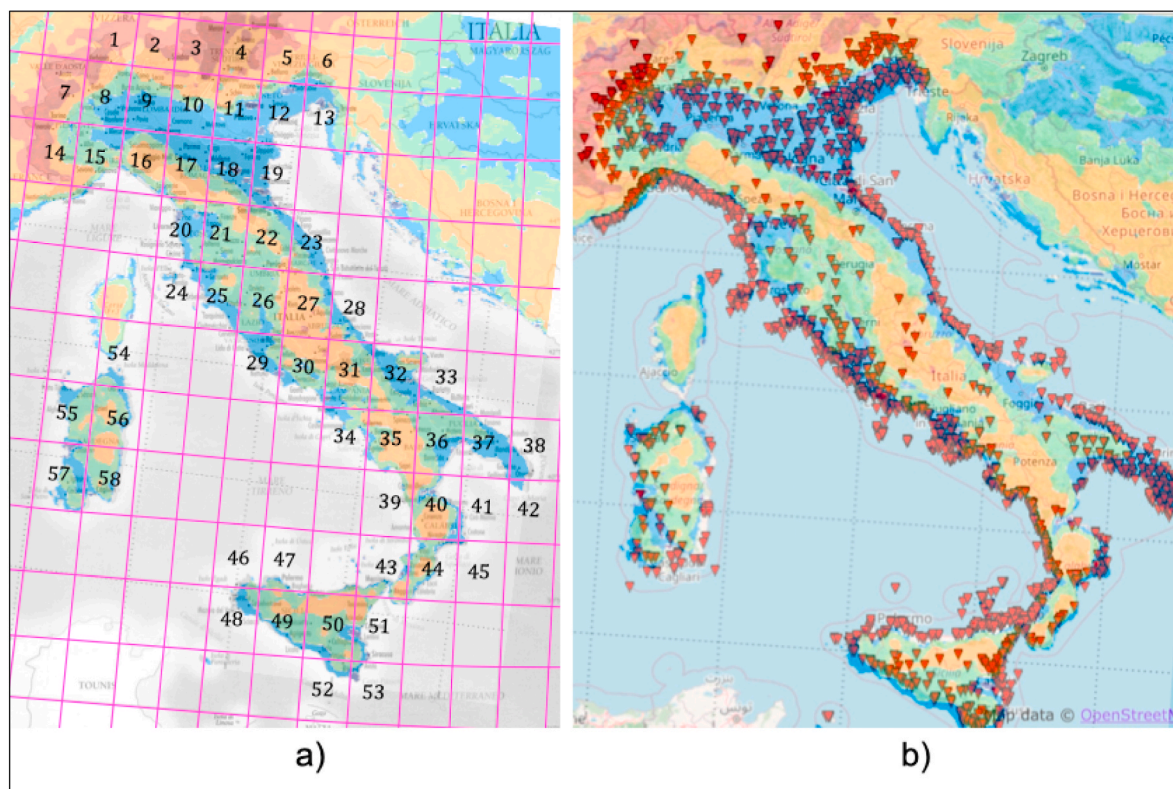


Fig. 2. a) Subdivision of the Italian territory into cells according to the grid identified by the meridians and parallels. b) Map of tornado events that occurred from 1970 to date extracted from the ESWD.

geographical NaTech risk for tornado/wind gusts (Table 1). Moreover, by maintaining a more conservative approach, the lower score limits of each level are included, while the upper ones are excluded.

- NEGLIGIBLE GEOGRAPHICAL RISK level, corresponding to a situation in which the maximum frequency of EF1 events is recorded, with a score ranging from 0 % to 4.7 % of the maximum score, corresponding to a screening score between 0 and 3 (excluded).
- LOW GEOGRAPHICAL RISK level, corresponding to a situation in which the maximum frequency of EF1 and EF2 events is recorded, with a score ranging from 4.7 % to 14.2 % of the maximum score, corresponding to a screening score between 3 (included) and 9 (excluded).
- MEDIUM GEOGRAPHICAL RISK level, corresponding to a situation in which the maximum frequency of EF1, EF2 and EF3 events is recorded, with a score ranging from 14.2 % to 28.5 % of the maximum score, corresponding to a screening score between 9 (included) and 18 (excluded).
- HIGH GEOGRAPHICAL RISK level, corresponding to a situation in which the maximum frequency of EF1, EF2, EF3 and EF4 events is recorded, with a score ranging from 28.5 % to 47.5 % of the maximum score, corresponding to a screening score between 18 (included) and 30 (excluded).
- SEVERE GEOGRAPHICAL RISK level, corresponding to a situation in which the maximum frequency of EF1, EF2, EF3, EF4, EF5 and EF6 events is recorded, with a score ranging from 47.5 % to 100 % of the maximum score, corresponding to a screening score between 30 (included) and 63 (included).

For industrial facility that are assigned in the screening phase a geographical risk level equal to or greater than “MEDIUM GEOGRAPHICAL RISK” (score ≥ 9) the method involves proceed to the second step of the analysis: the identification of danger zones and critical equipment.

2.2. Identification of danger zones and critical equipment

The second step of the methodology builds primarily on the work of Necci and Krausmann (2022), which provides, based on historical investigation, a comprehensive overview of damage mechanisms affecting different types of equipment under various NaTech scenarios. The conclusions are condensed into two tables (Tables S6 and S7 of the Supplementary Materials), respectively associate natural hazards with damage modes, and equipment categories with their potential damage mechanisms.

By selecting only damage modes relevant to strong wind gusts and tornadoes, and cross-referencing them with susceptible equipment categories, a specific damage matrix (Table 2) is derived. This table associates each type of asset with the damage mechanisms that may occur under extreme wind conditions and constitutes the basis of the present analysis.

While from the document of Necci and Krausmann information

Table 1
Matrix of Geographical NaTech risk for tornado/wind gusts.

| Geographical risk level | Minimum score | Maximum score |
|-------------------------|---------------|---------------|
| Negligible | 0 | < 3 |
| Low | 3 | < 9 |
| Medium | 9 | < 18 |
| High | 18 | < 30 |
| Severe | 30 | 63 |

about the vulnerability of the specific equipment were drawn, the methodological approach adopted for the tornado-related NaTech risk assessment partially draws on the index-based methodology developed by Giannelli et al. (2020), or earthquake-induced NaTech scenarios. In particular, the use of qualitative indices and their combination within a risk matrix is retained.

In this framework, tornado-related NaTech risk is defined as the probability that an industrial installation experiences damage of a given severity, as a function of: (i) the characteristics of the natural hazard (frequency and intensity), (ii) the vulnerability of the impacted equipment, and (iii) the severity of the consequences for safety, the environment, and business continuity.

Accordingly, a Risk Index (RI) is defined for each *i*-th piece of equipment or danger zone and for each impact category *j* (safety, environment, business), as:

$$RI_{ij} = PI_i \times MI_{ij} \tag{2}$$

Where PI_i is the Probability Index for the equipment *i* and MI_{ij} is the Magnitude Index for the equipment *i* with respect to the impact category *j* (safety, environment, business).

The Probability Index is defined as a function of two contributions.

- the Geographical Risk Index ($GRI_{screening}$), which account for the expected frequency of a tornado/strong gusts of wind of a certain intensity on the investigated site. It is derived from the Screening Score obtained in Step 1 according to the criteria shown in Table S8 of the Supplementary Materials;
- the Vulnerability Index (*VI*) of the individual equipment.

The Magnitude Index accounts for the severity of the consequences associated with the release scenario and is evaluated qualitatively according to the severity of the scenario, which may vary depending on the quantities and characteristics of the substance released.

The expression of the Risk Index reported in eq. (2) can therefore be rewritten as follows:

$$RI_{ij} = f(GRI_{screening}; VI) \times MI_{ij} \tag{3}$$

All the indices, and the evaluation of their score, will be discussed in detail below.

2.2.1. Vulnerability Index

When a natural hazard impacts an industrial site, different process units may experience significantly different consequences depending on their structural characteristics (geometry, dimensions, construction materials, wall thickness), operational conditions (e.g., filling level), location within the plant layout, and the presence of protective measures such as anchoring systems.

This variability is captured by the Vulnerability Index (*VI*), defined for each piece of equipment as the product of three coefficients:

$$VI = F_M \times C_w \times C_f \tag{4}$$

The meaning of each of the three coefficients is analyzed below. The coefficients are calibrated so that the Vulnerability Index ranges between 1 and 5, in line with Giannelli et al. (2020).

- F_M – *failure mode coefficient*: accounts for the number of potential damage modes affecting the equipment: the more numerous the possible damage mechanisms that the equipment can suffer (indicated with an *x* in Table 2), the higher F_M .
- C_w – *wind coefficient*: This coefficient provides an indication of the asset vulnerability according to the minimum wind speed capable of damaging it. The wind coefficient C_w is assigned using a qualitative approach, due to the lack in literature of fragility curves correlating wind speed and damage probability for most industrial equipment. Reference damage modes associated with EF1, EF2, and EF3 events

Table 2
Damage modes relevant for different processes and storage equipment in case of tornado/strong wind gusts (information from [Giannelli et al. \(2020\)](#)).

| | Atmospheric storage tank | Pressurised vessel (bullet/sphere) | Heat exchanger | Phase separator | Atmospheric column | Pressurised column | Stack | Others |
|----------------------------------|--------------------------|------------------------------------|----------------|-----------------|--------------------|--------------------|-------|--------|
| Buckling | X | | | | X | | X | |
| Rupture of pipes and connections | X | X | X | X | X | X | | |
| Tearing | X | | | | | | | |
| Fixed roof damage | X | | | | | | | |
| Floating roof damage | X | | | | | | | |
| Displacement | X | X | | X | | | | |
| Overturning | X | X | | X | X | X | | |
| Puncturing damage | X | | | | | | | |

are reported in [Table S9](#) of the Supplementary Materials. Then, depending on the damage mode to which each equipment can be susceptible, a C_w equal to 0.75 or 1 is assigned. During events classified as EF1 losses from pipes and connection/instrumentation and fragments projection (referred to as “puncturing damage”) are assumed: supposing the presence of connections and instrumentation in each equipment, the EF1 event category does not lead to a more significant risk for one equipment than another. Equipment susceptible to damage already at EF2 intensity is assigned a C_w equal to a coefficient 1, while equipment requiring EF3 or higher intensities is considered less vulnerable and therefore are associated with a lower wind coefficient, $C_w = 0.75$.

- C_f – *conditioning factors coefficient*: it reflects mitigating features that reduce the likelihood of buckling, overturning, or displacement. Values between 0.8 and 0.9 are recommended as shown in [Table S10](#) of the Supplementary Materials, although the final choice is left to the analyst.

The values of the coefficients to be assigned to each equipment are given in [Table 3](#). The last row shows both the minimum value of VI , obtained by multiplying F_M , C_w and $C_{f_{min}}$ and the maximum value, which is obtained by assuming no presence of safety beneficial factors, and considering therefore unitary the conditioning factors coefficient. The values considered are directly related to the actual state of each piece of equipment, even if possibly affected by a bias related to the presence of hard-adaptive measures on the territory, which may have induced a reduction in the protective measures ([Logan et al., 2018](#)). Anyway, at the moment, there is no evidence of the presence of such mitigation measures on the territory taken in examination.

2.2.2. Probability Index

The two indices just presented, the Geographical Risk Index and the Vulnerability Index, are combined and the average of the two is assigned the name of “Probability score”, according to which each i -th process unit will be assigned a Probability Index, PI .

Table 3
Values of the F_M , C_w and $C_{f_{min}}$ coefficients to be assigned to each equipment.

| | Atmospheric storage tank | Pressurised vessel (bullet/sphere) | Heat exchanger | Phase separator | Atmospheric column | Pressurised column | Stack | Others |
|----------------------------------|--------------------------|------------------------------------|----------------|-----------------|--------------------|--------------------|-------|--------|
| Buckling | X | | | | X | | X | |
| Rupture of pipes and connections | X | X | X | X | X | X | | |
| Tearing | X | | | | | | | |
| Roof damage | X | | | | | | | |
| Displacement | X | X | | X | | | | |
| Overturning | X | X | | X | X | X | | |
| Puncturing damage | X | | | | | | | |
| F_M | 5 | 4 | 2 | 4 | 4 | 3 | 2 | 1 |
| C_w | 1 | 0.75 | 1 | 0.75 | 1 | 0.75 | 1 | 1 |
| $C_{f_{min}}$ | 0.8 | 0.85 | 0.9 | 0.9 | 0.8 | 0.85 | 0.85 | 1 |
| VI | 4 | 2.3 | 1.8 | 2.7 | 3.2 | 1.9 | 1.7 | 1 |
| | – | – | – | – | – | – | – | – |
| | 5 | 3 | 2 | 3 | 4 | 2.3 | 2 | |

$$PROBABILITY\ SCORE = \frac{GRI_{screening} + VI}{2} \tag{5}$$

Since both $GRI_{screening}$ and VI ranges from 1 to 5, their average may spans the same interval. This interval is divided into five equal classes (width 0.8) to assign a discrete Probability Index (PI), as reported in [Table S11](#) of the Supplementary Materials.

2.2.3. Magnitude Index

The mere occurrence of a loss of containment is not sufficient to characterize the severity of an accident scenario. Both the release rate and the physicochemical properties of the substance must be considered. Moreover, the same scenario may have different implications for worker safety, environmental damage, and business continuity.

For this reason, the Magnitude Index (MI) is evaluated separately for each j -th impact categories: safety, environment, and business. Following the approach proposed by [Giannelli et al. \(2020\)](#), five severity levels are defined for each category, ranging from negligible to catastrophic. Example criteria for assigning Magnitude Index values are provided in [Table S12](#) of the Supplementary Materials; however, the final attribution remains the responsibility of the analyst.

When choosing the value to be attributed to the MI_{safety} , the effects on workers (On-Site) and on the population around the plant (Off-Site) must be considered together. While under the business aspect fall both property damage, caused by the direct impact of the natural phenomenon and quantifiable mostly in terms of repair costs and/or replacement of the damaged asset; both the economic losses deriving from shutdowns of plant and the relative non-production, quantifiable in terms of downtime. [Table S12](#) of the Supplementary materials shows by way of example a possible subdivision and attribution criteria for assigning magnitude levels, the consequences can vary from mild/negligible to catastrophic. This is however a purely indicative table of the type normally used during qualitative risk analysis (e.g., HAZOP and HAZID workshops). Differences usually concern the numerical ranges associated with each class (e.g., economic loss, number of injuries or fatalities,

environmental impact), which are often defined or tailored according to client-specific criteria and corporate risk policies.

2.2.4. Risk Index

The distinction made by impact areas in the magnitude assessment results also in the attribution of three different Risk Indices (RI) - one for each *j*-th impact area (safety, environment, and business) - to each *i*-th equipment present in the plant.

$$RI_{ij} = PI_i \times MI_j \tag{6}$$

Given that both the Probability Index and the Magnitude Index range from 1 to 5, the Risk Index spans integer values from 1 to 25, thus generating the 5x5 Risk Matrix shown in Table 4.

This qualitative, index-based methodology enables an objective comparison among different units within the same plant, allowing the identification of critical equipment and supporting the prioritization of mitigation and prevention measures for NaTech risk induced by extreme wind events.

2.3. Quantitative analysis

The last step of the of the proposed methodology consists of the quantitative evaluation of the accidental scenarios associated with the critical equipment identified in the previous step. The objective of this phase is to quantify both components contributing to the determination of risk, i.e., frequency and magnitude.

This step is presented here only in general terms, as it largely follows established procedures used in conventional technological risk analyses. A detailed treatment of the quantitative analysis lies beyond the scope of the present work.

The frequency of occurrence of a NaTech event is defined by (UNI/TS 11816-1:2021) as the product between the frequency of the natural event and the probability of damage to critical equipment. The frequency of the natural event has already been partially evaluated during the historical analysis performed in the preliminary screening phase. However, this approach does not account for the different spatial extents of the investigated cells, and, for QRA purposes, a precise impact frequency is required. For the same reason, it is also necessary to define a geometrically based impact probability that accounts for both the facility dimensions and, most importantly, the area typically affected by the passage of a tornado.

Impact is defined as the geometric intersection between the facility footprint and the area affected by the tornado track. The impact probability of a single event is approximated using an effective interaction area equal to the sum of the facility area A_{plant} and the mean affected area of a class-*n* tornado, $A_{tornado_{EF_n}}$. This represents a first-order

approximation of the interaction between two extended objects and is commonly adopted in spatial hazard analyses.

The resulting annual impact frequency can therefore be expressed, under the assumptions of spatial homogeneity, event independence, and representative average tornado track characteristics, as:

$$f_{normalized_{EF_n}} = \frac{N_{EF_n} \cdot A_{plant} + A_{tornado_{EF_n}}}{T \cdot A_{cell}} \tag{7}$$

Where the first ratio is the frequency of occurrence of the *n*-th class of the Enhanced Fujita scale of natural event affecting the survey area, as the term N_{EF_n} indicates the number of tornadoes of class-*n* observed during the reference period *T*. A_{plant} is the area of the industrial facility, A_{cell} is the area of the geographical cell used for the historical analysis and $A_{tornado_{EF_n}}$ is the average impact surface of a class-*n* tornado, which can be estimated starting from the mean values of path length and width reported in several studies (Brooks, 2004; Elsner et al., 2014).

With respect to the probability of damage to the equipment, UNI/TS 11816-1:2021 identifies parametric methods and empirical correlations – such as fragility curves – as reference tools to relate the intensity of the natural hazard to the expected level of damage. However, due to the limited availability of data in the scientific literature concerning tornadoes and strong wind gusts and given that existing studies are restricted to specific equipment and damage modes, a simplified binary approach is adopted in this work. In this approach, the occurrence of a specific damage mode is assumed to be certain once a threshold wind speed is exceeded.

Based on the damage classification reported in Table S9 of the Supplementary Materials, the following assumptions are made.

- For wind speeds exceeding 138 km/h, damage is assumed to occur to all equipment due to failures of pipes, connections, and instrumentation, as well as puncturing damage caused by windborne debris. This condition is assumed to result in a continuous release through an equivalent hole of 10 mm diameter, which can be classified as a moderate release;
- for wind speeds exceeding 178 km/h, more severe consequences are assumed for all equipment, as all assets may experience rupture of connections. In this case, a significant release is considered, either in the form of a full-bore rupture (i.e., a release from an opening equal to the pipe diameter) or, alternatively, as the release of the entire equipment hold-up within 10 min;
- for wind speeds exceeding 218 km/h, catastrophic damage mechanisms such as overturning and displacement are also considered likely. These failure modes are assumed to result in an almost instantaneous release of the entire inventory.

A comparable approach based on discrete damage states (DS) has been adopted by Campedel et al. (2008), for the development of a seismic NaTech quantitative risk assessment methodology. In that work, three damage states were defined for tanks and pipelines, and the most severe states (DS2 and DS3) were associated with specific magnitudes of loss of containment (LOC) and with corresponding accident scenarios, referred to as risk states (RS). Specifically, for atmospheric storage tanks, DS2 was associated with a leak with a diameter of 50 mm (RS2), while DS3 corresponded to catastrophic vessel failure and near-instantaneous loss of the entire inventory (RS3). For pressurised vessels, DS2 was associated with the release of the entire inventory within 10 min (e.g., due to full-bore rupture of a main connection), whereas RS3 corresponded to an almost instantaneous release.

In the present methodology, the choice of release flow rates associated with each wind intensity category was not arbitrary but aimed at ensuring consistency and integration between NaTech-induced scenarios and conventional technological accident scenarios typically considered in quantitative risk analyses (e.g., scenarios triggered by sensor failures, deviations from operating conditions, loss of utilities, or

Table 4

Risk matrix relating to the *i*-th equipment and the *j*-th impact area (safety, environment, business).

| IR _i | | IP | | | | |
|-----------------|----------------------|----------------------|-----------------------------|-------------------------|------------------------------|-----------------------|
| | | Low probability 1 | Medium low probability 2 | Medium probability 3 | Medium high probability 4 | High probability 5 |
| IM _j | 5 - Catastrophic | ML 5 | MH 10 | H 15 | VH 20 | VH 25 |
| | 4 - Severe | ML 4 | MH 8 | H 12 | VH 16 | VH 20 |
| | 3 - Extreme serious | L 3 | ML 6 | MH 9 | H 12 | H 15 |
| | 2 - Serious | L 2 | ML 4 | ML 6 | MH 8 | MH 10 |
| | 1 - Minor/Negligible | L 1 | L 2 | L 3 | ML 4 | ML 5 |

Note: L = Low; ML = Medium – Low; M = Medium; MH = Medium – High; H = High; VH = Very High.

human error). By aligning the ultimate consequences of NaTech and conventional scenarios, both types of events can be characterized by comparable magnitudes, allowing their integration and superposition within the same risk framework.

Ultimately, the goal of the NaTech quantitative analysis is to include the effects of natural hazards among the possible initiating causes of accidental scenarios. This is achieved by summing the frequencies associated with NaTech-initiated events and those derived from conventional technological failures, resulting in an increased overall probability of occurrence for the corresponding accident scenarios.

3. Results

The proposed methodology was applied to a real industrial case study consisting of a natural gas processing facility used to treat natural gas extracted from offshore platforms (Fig. 3).

For the first application, the facility was assumed to be located in Italy, in the Puglia region (the exact geographical position of the plant is reported in Fig. S1 of the Supplementary Materials); then a sensitivity analysis to the location was performed by applying again the methodology to the same facility hypothetically located in other five additional sites, both in Italy and in the United States.

For the analysis the input data and tools reported in the first column of Fig. 1 have been used, namely geographical information, reports from the ESWD, plant layout, equipment information, and substance properties.

3.1. Territorial characterization and screening analysis

The first step of the analysis consisted of the territorial characterization of the site, performed using data extracted from the European Severe Weather Database (ESWD). A survey period of 50 years was considered, from January 01, 1973 to May 08, 2023. Since the facility is located close to the boundary between grid cells 37 and 38, the historical analysis was extended to include both cells, resulting in an investigated area of approximately 18,000 km², bounded by the 40th and 41st parallels north and the 17th and 19th meridians east. The total number of extracted tornado and strong wind gust events was therefore halved for

each category.

The number of the recorded events, their classification according to the Enhanced Fujita scale (or virtual < EF0 class), the corresponding frequencies, intensity indices, and frequency indices are summarized in Table 5.

Based on the classification criteria defined in Table 1 and on the resulting Screening Score, the site was assigned a High Geographical Risk level. Consequently, the analysis proceeded to the second step, namely the identification of danger zones and critical equipment within the plant. The Screening Score also led to the attribution of a Geographical Risk Index ($GRI_{screening}$) equal to 3, in accordance with Table S8 of the Supplementary Materials.

3.2. Identification of critical equipment and vulnerability assessment

Natural gas arriving at the facility is saturated with water under reservoir conditions; therefore, dehydration treatment is required to meet the dew-point specifications for delivery to the national gas distribution network. To this end, the plant includes two phase separators, three dehydration columns operating with triethylene glycol (TEG), and one gas flare. In addition, several storage tanks are present for glycol, water, and gasoline, together with various auxiliary equipment such as pumps, filters, compressors, and heat exchangers.

The vulnerability analysis was carried out in accordance with the methodology described in Section 2.2, using the coefficients reported in Table 3. For each item of equipment, the Vulnerability Index (VI) was calculated according to Eq. (4), and the corresponding Probability Index (PI) was determined using Eq. (5).

Magnitude indices for the three impact categories (safety, environment, and business) were then assigned based on the qualitative criteria reported in Table S12 of the Supplementary Materials. As discussed previously, the final attribution of magnitude levels remains at the discretion of the analyst and may be adapted to site-specific conditions.

Finally, for each piece of equipment, three Risk Indices were computed, one for each impact category. The results of the risk assessment for the case study plant located in the Puglia region are reported in Table 6.



Fig. 3. Satellite image of the case study plant located in the Puglia region (the different plant area are colored in different way as explicated in Table &).

Table 5

Classification of tornado and strong wind gusts events extracted from the ESWD for the plant location and corresponding Screening Score (color coded according to Table 1).

| Event Classification | Intensity Index (II) | Number of recorderd events | Frequency [ev/year] | Frequency Index (FI) | II X IF |
|--|----------------------|----------------------------|---------------------|----------------------|-----------|
| $v_w < 105 \text{ km/h}$ (< EF0) | 1 | 22,5 | 0,45 | 2,5 | 2,5 |
| $105 < v_w < 137 \text{ km/h}$ (EF0) | 2 | 47 | 0,94 | 3 | 6 |
| $138 < v_w < 177 \text{ km/h}$ (EF1) | 3 | 8 | 0,16 | 2 | 6 |
| $178 < v_w < 217 \text{ km/h}$ (EF2) | 4 | 2 | 0,04 | 1 | 4 |
| $218 < v_w < 266 \text{ km/h}$ (EF3) | 5 | 1 | 0,02 | 0,5 | 2,5 |
| $v_w > 267 \text{ km/h}$ (\geq EF4) | 6 | 0 | 0 | 0 | 0 |
| Screening score | | | | | 21 |

3.3. Discussion of results for the reference location

The results highlight that the most critical equipment, characterized by non-negligible risk levels, includes vertical structures such as the derrick flare stack and the TEG dehydration columns, as well as phase separators processing hydrocarbons and gasoline storage tanks. For these assets, a more detailed quantitative risk analysis would be appropriate to better quantify both occurrence probabilities and potential consequences.

Exceptions may reasonably be made for water and glycol storage tanks. Although these units exhibit relatively high vulnerability due to their structural characteristics, the substances they contain are not hazardous. Consequently, their associated safety and environmental risk levels remain limited despite the structural susceptibility of the equipment.

3.4. Sensitivity analysis to the location

To better contextualize and evaluate the robustness of the methodology, a sensitivity analysis to the location was performed. The same facility was hypothetically relocated to five additional sites: four in Italy (Bussi sul Tirino in the Pescara province, Milazzo in the Messina province, Livorno, and Marghera in the Venezia province) and one in the United States (Oklahoma City, Oklahoma). The geographical positions of the Italian sites are shown in Fig. S1 of the Supplementary Materials.

For the U.S. location, the territorial characterization was carried out considering a period of 72 years and by using the “tornado tracks tool”, an interactive map developed by the Midwestern Regional Climate Center, based on data provided by the Storm Prediction Center (SPC), which collects tornado events occurred all around the United States. Fig. S2 of the Supplementary Materials shows the spatial distribution of tornado events recorded in the survey area. Unlike the ESWD, the U.S. database does not allow filtering events by exact coordinates. Therefore, events were manually extracted by centering the investigated site within a rectangular area comparable in size to the Italian grid cells, approximately 12,000 km². Moreover, the database only reports events classified as EF0 or higher, as strong wind gusts without confirmed tornado formation are not included.

Despite this limitation, since Oklahoma City is located in the so-called “Tornado Alley”, a central region of the United States characterized by one of the higher frequency of tornado formation in the world (Maas et al., 2024), the screening analysis still clearly indicates a significantly higher geographical risk level compared to all Italian locations considered.

Table 7 summarizes the complete historical analysis for each site, including extracted events, calculated Screening Scores, corresponding Geographical Risk Indices, and the results of the equipment-level risk assessment.

The sensitivity analysis clearly demonstrates how the risk level associated with individual equipment varies as a function of plant location. Highly vulnerable assets, such as flare stacks, columns, and gasoline storage tanks, consistently exhibit medium to high risk levels across all investigated sites, confirming the need for further in-depth analysis regardless of geographical context. Conversely, other equipment items, including pumps and phase separators, show a marked variability in their Risk Indices depending on the geographical risk level of the site. This behavior highlights the capability of the proposed methodology to discriminate among different territorial conditions and to reflect the expected statistical incidence of extreme wind events. Overall, the results confirm the effectiveness of the methodology as a screening tool for tornado-related NaTech risk, capable of identifying both critical equipment within a plant and locations requiring more detailed quantitative investigations.

4. Conclusion

Extreme meteorological events characterized by intense wind action, such as tornadoes and hurricanes, can severely affect industrial installations, triggering powerful mechanisms of both direct and indirect releases of hazardous materials. For this reason, their potential impact should be explicitly accounted for within industrial risk assessment frameworks.

This study aimed to address a gap in the current NaTech risk assessment literature by proposing a qualitative methodology specifically designed to evaluate the risk associated with tornadoes and severe wind gusts. To the authors’ knowledge, no dedicated and comprehensive methodology addressing this hazard–technology interaction had previously been made available.

The proposed methodology enables analysts to perform a preliminary assessment of the risk level associated with an industrial facility, starting from the statistical incidence of extreme wind events at the territorial level and progressing toward the identification of the most critical equipment within the plant. The approach was applied to a real case study involving a natural gas processing facility and was subsequently tested through a sensitivity analysis in which the same plant was hypothetically located in five additional sites, four in Italy and one in the United States. The results demonstrate the effectiveness of the methodology to discriminate among different territorial risk conditions and

Table 6

Results of the tornado-related Na-Tech risk assessment for the case-study plant located in Puglia region. Risk Index are colored following Table 4. Plant Area is color coded in consistency with Fig. 3.

| EQUIPMENT | | PLANT AREA Of Figure 3 | NOTE | VULNERABILITY | | | | PROBABILITY | | MAGNITUDE | | | RISK | | | |
|-----------|--|------------------------|----------------------------------|---------------|------|------|------|-------------|----|-----------|-----|-----|------|-----|-----|--|
| ID | DESCRIPTION | | | FM | Cw | Cf | VI | Prob score | PI | Mls | Mle | Mls | Rls | Rle | Rib | |
| F-001 | Derrick flare stack | Yellow | external, anchored | 2 | 1 | 1 | 2.00 | 2.5 | 2 | 4 | 1 | 3 | 8 | 2 | 6 | |
| FL-001 | Liquid seal | | / | 1 | 1 | 1 | 1.00 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 4 | |
| C-001 | Dehydration column with TEG | Pink | internal, unanchored | 3 | 0.75 | 0.95 | 2.14 | 2.57 | 2 | 4 | 1 | 4 | 8 | 2 | 8 | |
| C-002 | | | | | | | | | | | | | | | | |
| C-003 | | | | | | | | | | | | | | | | |
| F-001 | TEG filters | Orange | / | 1 | 1 | 1 | 1.00 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | |
| F-002 | | | | | | | | | | | | | | | | |
| F-003 | Dust filter | Orange | / | 1 | 1 | 1 | 1.00 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | |
| PT-001 | Pumps with TEG | | / | 1 | 1 | 1 | 1.00 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 4 | |
| PT-002 | | | | | | | | | | | | | | | | |
| PT-003 | | | | | | | | | | | | | | | | |
| PG-001 | Pumps with gasoline | Orange | / | 1 | 1 | 1 | 1.00 | 2 | 2 | 3 | 2 | 2 | 6 | 4 | 4 | |
| PG-002 | | | | | | | | | | | | | | | | |
| AT-T-01 | Atmospheric storage tank with TEG | Blue | external, small size, unanchored | 5 | 1 | 0.85 | 4.25 | 3.63 | 4 | 1 | 1 | 2 | 4 | 4 | 8 | |
| AT-T-02 | | | | | | | | | | | | | | | | |
| AT-T-03 | | | | | | | | | | | | | | | | |
| AT-W-01 | Atmospheric storage tank with water | Blue | external, small size, unanchored | 5 | 1 | 0.9 | 4.50 | 3.75 | 4 | 1 | 1 | 2 | 4 | 4 | 8 | |
| AT-G-01 | Atmospheric storage tank with gasoline | | external, small size, unanchored | 5 | 1 | 0.9 | 4.50 | 3.75 | 4 | 4 | 1 | 2 | 16 | 4 | 8 | |
| PS-T-01 | Phase separator wet TEG | Green | external, unanchored | 4 | 0.75 | 1 | 3.00 | 3 | 3 | 1 | 1 | 1 | 3 | 3 | 3 | |
| PS-T-02 | | | | | | | | | | | | | | | | |
| PS-H-01 | Phase separator hydrocarbons | Green | external, unanchored | 4 | 0.75 | 1 | 3.00 | 3 | 3 | 3 | 1 | 1 | 9 | 3 | 3 | |
| PS-H-02 | | | | | | | | | | | | | | | | |
| PS-H-03 | Fuel gas phase separator | Green | external, unanchored | 4 | 0.75 | 1 | 3.00 | 3 | 3 | 4 | 1 | 2 | 12 | 3 | 6 | |
| HE-T-01 | TEG cooling | | external, unanchored | 2 | 1 | 1 | 2.00 | 2.5 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | |
| K-001 | Compressors | Purple | / | 1 | 1 | 1 | 1.00 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 4 | |
| K-002 | | | | | | | | | | | | | | | | |

Note: RIs = Safety Risk Index; Rle = Environmental Risk Index; Rib = Business Risk Index.

to identify critical assets in a manner consistent with the expected statistical incidence of tornado events.

As expected, the case study located in Oklahoma City exhibited the highest overall Risk Index. However, despite being situated in the core of the so-called “Tornado Alley”, commonly recognized as one of the regions worldwide most exposed to tornadoes, the associated Screening Score did not reach the theoretical maximum value. This outcome suggests that the assumptions adopted in defining intensity and frequency indices are balanced and not excessively conservative. Although some parameters are necessarily based on expert judgment, the application of the methodology to multiple locations confirms a posteriori the robustness and internal consistency of the proposed framework.

One of the main advantages of the methodology lies in its limited data and resource requirements. The analysis relies on readily available information, including historical wind event databases and basic plant data such as layout, equipment type, and stored substances, making it particularly suitable for screening purposes and early-stage risk evaluations.

Nevertheless, the methodology is affected by limitations, primarily

due to the lack of studies on the interactions between strong wind gusts and industrial equipments. As a consequence, several simplifying and, in some cases, conservative assumptions were introduced. For instance, the selection of relatively large survey areas in the historical analysis, while consistent with the structure of the ESWD and effective in capturing events occurring in morphologically similar regions, may lead to an overestimation of the actual exposure of a specific plant to tornado events. However, in the context of a qualitative screening methodology, such conservatism is preferable to the risk of excluding potentially critical situations at an early stage. The subsequent quantitative analysis phase offers the opportunity to normalize event frequencies and refine the risk estimation.

Additional simplifications concern the extent and severity of the assumed damage mechanisms. Although these assumptions are partially supported by available literature (Necci et al., 2018; Stevenson et al., 2023) and by the professional experience of the analysts involved, they may result in the identification of equipment as critical that would not necessarily experience severe damage in reality, leading to an overestimation of risk. However, the absence of fragility curves correlating

Table 7

Results of the tornado-related NaTech risk assessment for the case study plant located at five alternative sites. Screening Scores are colored according to Table 1, Probability Indices according to Table S8, and Risk Indices according to Table 4.

| GEOGRAPHICAL RISK LEVEL | | | | | | | | | | | | | | | | |
|--|-----------------------|------|-----|--------------|------|----|---------|------|-----|---------------|------|----|--------------------|------|-----|--|
| EVENT | Bussi sul Tirino (PE) | | | Milazzo (ME) | | | Livorno | | | Marghera (VE) | | | Oklahoma City (OK) | | | |
| | ev | fr | FI | ev | fr | FI | ev | fr | FI | ev | fr | FI | ev | fr | FI | |
| EVENT $v_W < 105 \text{ km/h}$ ($< EF0$) | 20 | 0.4 | 2,5 | 29 | 0.58 | 3 | 58 | 1.16 | 3 | 176 | 3.52 | 3 | n.a. | n.a. | 0 | |
| EVENT $105 < v_W < 137 \text{ km/h}$ ($EF0$) | 10 | 0.2 | 2 | 71 | 1.42 | 3 | 75 | 1.5 | 3 | 93 | 1.86 | 3 | 179 | 2.49 | 3 | |
| EVENT $138 < v_W < 177 \text{ km/h}$ ($EF1$) | 0 | 0 | 0 | 1 | 0.02 | 1 | 12 | 0.24 | 2,5 | 14 | 0.28 | 2 | 189 | 2.63 | 3 | |
| EVENT $177 < v_W < 217 \text{ km/h}$ ($EF2$) | 1 | 0.02 | 0.5 | 0 | 0 | 0 | 4 | 0.08 | 1 | 4 | 0.08 | 1 | 110 | 1.53 | 3 | |
| EVENT $218 < v_W < 266 \text{ km/h}$ ($EF3$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0.04 | 1 | 38 | 0.52 | 3 | |
| EVENT $v_W > 266 \text{ km/h}$ ($\geq EF4$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0.04 | 1 | 19 | 0.26 | 2.5 | |
| Screening Score | 8.5* | | | 12 | | | 20.5 | | | 30 | | | 57 | | | |
| $PI_{\text{screening}}$ | | | | 1 | | | 3 | | | 4 | | | 5 | | | |

| RISK INDEX | | | | | | | | | | | | | | |
|----------------|--|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|--------------------|-----------------|-----------------|--|
| ID | EQUIPMENT DESCRIPTION | Milazzo (ME) | | | Livorno | | | Marghera (VE) | | | Oklahoma City (OK) | | | |
| | | RI _s | RI _e | RI _b | RI _s | RI _e | RI _b | RI _s | RI _e | RI _b | RI _s | RI _e | RI _b | |
| F-001 | Derrick flare stack | 4 | 1 | 3 | 8 | 2 | 6 | 12 | 3 | 9 | 16 | 4 | 12 | |
| FL-001 | Liquid seal | 1 | 1 | 2 | 2 | 2 | 4 | 2 | 2 | 4 | 3 | 3 | 6 | |
| C-001/002/003 | Dehydration column with TEG | 4 | 1 | 4 | 8 | 2 | 8 | 12 | 3 | 12 | 16 | 4 | 16 | |
| F-001/2 | TEG filters | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | |
| F-003 | Pumps with TEG | 1 | 1 | 2 | 2 | 2 | 4 | 2 | 2 | 4 | 3 | 3 | 6 | |
| PT-001/002/003 | Pumps with gasoline | 3 | 2 | 2 | 6 | 4 | 4 | 6 | 4 | 4 | 9 | 6 | 6 | |
| PG-001/002 | Atmospheric storage tank with teg | 3 | 3 | 6 | 4 | 4 | 8 | 4 | 4 | 8 | 5 | 5 | 10 | |
| AT-T-01/02/03 | Atmospheric storage tank with water | 3 | 3 | 6 | 4 | 4 | 8 | 5 | 5 | 10 | 5 | 5 | 10 | |
| AT-W-01/02 | Atmospheric storage tank with gasoline | 12 | 3 | 6 | 16 | 4 | 8 | 20 | 5 | 10 | 20 | 5 | 10 | |
| AT-G-01 | Phase separator wet TEG | 2 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | |
| PS-T-01/02 | Phase separator hydrocarbons | 6 | 2 | 2 | 9 | 3 | 3 | 12 | 4 | 4 | 12 | 4 | 4 | |
| PS-H-01/02 | TEG cooling | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 4 | |
| PS-H-03 | Fuel gas phase separator | 3 | 3 | 6 | 4 | 4 | 8 | 5 | 5 | 10 | 5 | 5 | 10 | |
| HE-T-01 | Dust filter | 8 | 2 | 4 | 12 | 3 | 6 | 16 | 4 | 8 | 16 | 4 | 8 | |
| K-001/002 | Compressors | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | |

Note: RI_s = Safety Risk Index; RI_e = Environmental Risk Index; RI_b = Business Risk Index.

* For the site of Bussi sul Tirino (PE), the Screening Score remains below the threshold value of 9; therefore, according to the proposed methodology, no further equipment-level analysis is required for this location.

wind speed with damage probability for most types of industrial equipment necessitated the adoption of a qualitative, threshold-based approach.

Moreover, the adoption of equal weighting among indices is an

additional simplifying assumption, consistent with the screening-oriented and qualitative nature of the proposed methodology and with the current lack of consolidated quantitative evidence for tornado-related NaTech scenarios. This choice avoids introducing subjective

bias in the absence of robust weighting criteria and ensures transparency and reproducibility of the assessment. Unequal weighting could be implemented once more detailed damage statistics and vulnerability data become available, and this aspect is identified as a natural direction for future methodological developments.

In conclusion, the proposed methodology is intended as a preliminary screening tool capable of identifying industrial facilities and equipment exposed to potentially high tornado-related NaTech risk and, therefore, requiring a more detailed quantitative risk analysis. Future research efforts should focus on improving the understanding of the vulnerability of industrial equipment to extreme wind loads and on developing quantitative fragility models, which would allow a refinement of both the qualitative and quantitative stages of tornado-related NaTech risk assessment.

CRedit authorship contribution statement

Fabrizio Santamato: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Clara Iannantuoni:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Valentina Busini:** Writing – review & editing, Supervision, 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jlp.2026.105915>.

Data availability

Data will be made available on request.

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