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Definition of a NaTech risk analysis methodology for assessing tornado-related risk for storage tanks

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ABSTRACT

Natural catastrophic events, such as storms, earthquakes, flooding, and lightning; impacting industrial activities can trigger accidental scenarios, causing the release of hazardous substances from installations and storage, in events referred to as "Na-Tech" (Natural and Technological). Most of the attention in the literature has been devoted to accidents triggered by floods and earthquakes, while no specific analysis protocols aimed at determining the risk posed by tornadoes and strong gusts of wind on industrial facilities are available. Consequently, the purpose of this paper is to fill a gap in NaTech risk assessment, developing a qualitative methodology for the initial assessment of tornado-related Na-Tech risk for storage tanks, as previous works based on historical analysis have identified storages as the most critical asset, serving as a screening tool to determine which situations require a much more expensive Quantitative Risk Analysis (QRA). In the proposed methodology suitable Key Hazard Indicators (KHIs) were defined, requiring a limited amount of resources and information both on the intensity and frequency of the stormy event and on the plant and the characteristics of the assets in it, organizing them using the Analytical Hierarchy Process as a multi-criteria decision tool. In so doing, a specific Na-Tech risk level can be associated with a given situation (i.e., a process plant located in a given territory). The developed methodology was applied to a case study plant, and then a sensitivity analysis to both the locations and parameters was performed.

1. Introduction

If industrial sites are in naturally hazard-prone areas, the possible impact of a natural hazard can represent an additional potential initiating cause of incidental events, which must be considered along with the more classic "technological events", meaning with this term industrial accidents resulting from "internal" causes, such as design errors, malfunctions, or human operating errors. This potentially results in an increase in the frequency and intensity of the incidental scenarios associated with the release of hazardous substances [1].

Na-Tech scenarios have been studied over the past 40 years, as summarized in several reviews [2–4]. Research efforts have evolved from an initial focus on earthquake-related accidents to a growing interest in hydrometeorological hazards, particularly over the last two decades. This shift has been largely driven by climate change, which has increased the frequency and intensity of hydrometeorological events [3, 4]. A review of the literature reveals that most risk assessment methodologies have been developed for industrial accidents triggered by floods [5–7] and earthquakes [8–11] (only a few examples are cited here). Some studies have also addressed lightning-induced Na-Tech events, proposing specific risk assessment approaches for their management [12–14]. A limited number of works have explored the interaction between extreme winds and specific industrial assets [15–17]; however, there are currently no established protocols for assessing the risk posed by tornadoes and strong wind gusts to entire production facilities (i.e., comprehensive plant-wide risk assessment methodologies).

Nevertheless, according to Necci et al [18]. and Ricci et al [19]., earthquakes and floodings were responsible only for a contained percentage of the Na-Tech recordered, while the most frequent causes were found to be phenomena associated with extreme metereological events, such as lightning and strong wind [19,20].

The ultimate purpose of this paper is to fill a gap in NaTech risk assessment, carrying out a qualitative assessment of the NaTech risk level, in relation to extreme stormy phenomena, for atmospheric and pressurized tanks, as previous works based on historical analysis of past NaTech events have identified the storages as the most critical asset, also

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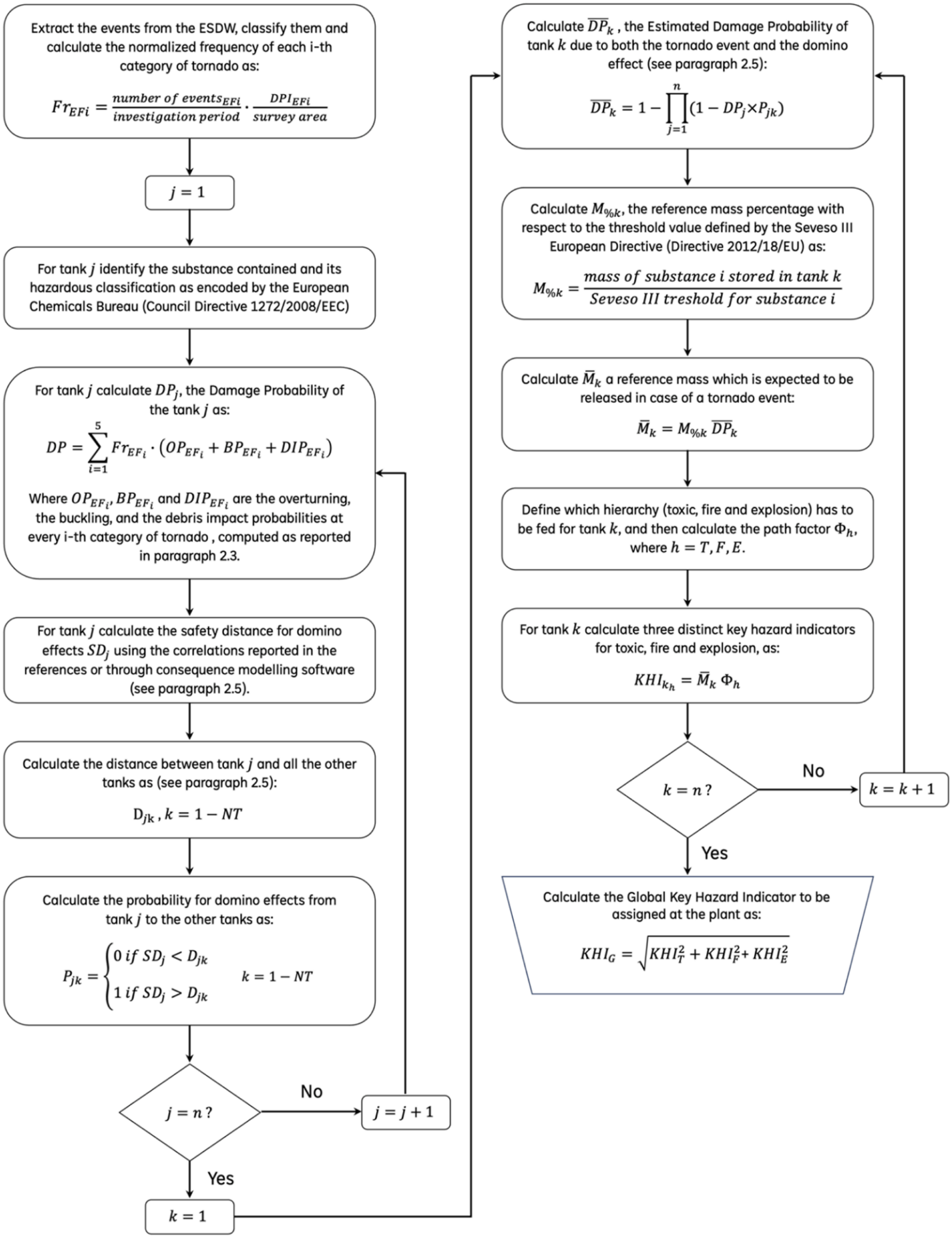

Figure 1. Procedure flowchart of the tornado-related Natech risk assessment for storage tank.

due to their high inventory [18,21–23]. Thus, identifying the situations that require further and more in-depth analysis, to be carried out with the Quantitative Risk Analysis (QRA) methods. In fact, QRA including, among the possible triggering causes of incidental events, also those of natural origin, represents the most powerful tool to evaluate the impact that a natural disaster may have on industrial facilities. However, it requires a large amount of information and resources both in economic and time terms. Hence the need for short-cut methodologies, easy to apply and requiring less resources and information.

To achieve the result, the most suitable methods to describe the probability of occurrence of the most characteristic accident scenarios of Na-Tech events generated by strong gusts of wind were searched in the literature. The most challenging part was finding a way to integrate all these methods so that they could communicate with each other. Given the significant differences among the variables in the model, both in nature and units of measurement, it was essential to organize and structure the quantities systematically. To achieve this, the Analytic Hierarchy Process (AHP), a multi-criteria selection method [24], was employed, as it has been previously applied in other Na-Tech risk analyses [5,8]. To adapt AHP to the qualitative risk analysis of Natech scenarios triggered by strong wind events, the integration of several methodologies—each with its assumptions and scope—required a thorough comparative evaluation and careful selection to ensure coherence and applicability. In this work, choices were made to guide the application of AHP in this context, tailoring it to produce a robust and practical tool that can now be applied in a matter of hours.

The procedure was applied to a case study plant. The chosen facility is assumed to be in Italy, in the Veneto region (i.e., one of the most windy region); then a sensitivity analysis to the location was carried out by applying again the methodology considering the plant as being located in other eight different sites, both in Italy and in the United States, as the methodology is generally applicable to any other region of the world once the statistical data on the natural event are available.

2. Methodology

The approach is divided into several phases that include:

- characterization of the natural event and historical analysis for the determination of the statistical incidence of tornadoes on the investigated territory.
- Identification of target equipments and their damage modes as a result of tornado impact.
- For each of the damage modes defined above, identification of functions that define the correlation between the intensity of the event and the probability of equipment failure; if these correlations are not available in the literature, probability of damage must be defined for the assets, based on past historical evidence and structural technical considerations.
- Identification of scenarios potentially generated by the release of materials stored and/or processed in damaged equipment, based on their hazardous characteristics.
- Definition of a method to assess the consequences of a domino effect and integration of the probability of its occurrence with the failure probability of individual equipment.
- Implementation of the Analytic Hierarchy Process (AHP) method to associate to the individual equipment, and then to the entire plant, a qualitative key performance indicator (KPI) indicative of the plant a risk level: low, ALARP (as low as reasonable possible), high.

A schematic summary flowchart of the procedure is shown in Figure 1.

2.1. Tornado event characterization and historical analysis

Tornadoes belong, as do cyclones (referred to by various terms as “hurricanes” or “typhoons” depending on the geographical area), to the category of storms and 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, although falling within the same weather classification, tornadoes and hurricanes differ strongly in several aspects, such as their genesis, the intensity of precipitation and wind gusts, duration of the event and extent of the affected area [25,26]. Therefore, their classification follows two different scales: while for hurricanes to date the Saffir-Simpson intensity scale is used [27], for tornadoes, several scales of intensity have been developed over time, such as the TORRO scale or the Fujita scale, modified and replaced in 2007 by its evolution, called “Enhanced Fujita scale”. Here the last one was taken as a reference and estimates the intensity of the tornado based on a series of damage indicators, classifying it in 6 categories, from EF0 to EF5 [28,29].

Among the various physical parameters that characterize the phenomenon, surely the wind speed appears to be the most indicative and most suitable to be taken into account in a risk analysis targeted on the effects on industrial equipment: the upper limit of the wind speed range for each category of the EF scale will be taken as a reference, starting with events classified as EF1, since wind gusts up to 137 km/h are not considered capable of causing significant damage to industrial assets [20]. An exception is made for category EF5, for which no indication of maximum speed is given, so it will be referred to that indicated in the same degree of intensity but in the version of the scale before 2007, i.e., tornado F5 - maximum wind speed 512 km/h.

Natural events that lead to disasters such as earthquakes, tornadoes and floods are always difficult to interpret and measure: the factors and variables that characterize the system are numerous and not always quantifiable, moreover, such phenomena have very low frequency of occurrence and are not predictable for most cases. For their study, simplifications were introduced that have led to characterizing the natural event through two main aspects: frequency of occurrence and severity.

As regard for Italian territory, maps of territorial zonation dividing the country into areas at isorisk compared to the specific natural hazard have been made for the danger of earthquakes [30] and floods [31]. Much less investigated are the extreme wind phenomena, to date, in fact, only works with a statistical analysis of the impact of tornadoes in Italy (from 1991 to 2000 [32] and from 2007 to 2016 [33]) or in Europe (from 1950 to 2013 [34] are present in literature but no updated territorial zonation is available of Italy in terms of the expected frequency of occurrence of tornado or strong wind gusts; therefore, as a first step of the Na-Tech risk analysis, an historical overview of the tornadoes that have affected the territory, where the investigated industrial plants are located, must be carried out. As a database for the historical analysis, the European Severe Weather Database (ESWD) was chosen since it appears to be the most suitable for the Italian territory. The ESWD [35] provides a large historical archive of natural events and uses an interactive map of the European territory with the possibility to set different search criteria (listed in the ANNEX 1 of Supplementary Materials). The Italian territory was divided into 58 cells by a grid that follows the terrestrial meridians and the terrestrial parallels (as shown in Figure S1a of the Supplementary materials), then latitude and longitude corresponding to the vertices of the grid cell, which the industrial plant falls in, are used for the survey. If the site falls close to the boundary between two or more cells, it is appropriate to extend the analysis by extracting the recorded events in all the proximal cells.

Table 1
Tornado intensity classification according to the Enhanced Fujita scale [41]. The statistically derived values of length and width (mean and median) of the tornado paths are reported from Elsner et al [37]. Using these values, average impact areas (eighth column) and DPIs (ninth column) were calculated.

Category	Wind Speed (m/s)	Number of recordered events	Path length (km)		Path width (m)		Surface a_i (km^2)	DPI (km^2)
			Mean	Median	Mean	Median	Mean	
EF0	[29 - 38]	4994	2.27	0.80	54.9	45.7	0.12	0.12
EF1	[38 - 49]	2624	7.10	4.39	163.8	91.4	1.16	2.32
EF2	[49 - 62]	818	14.29	10.03	344.1	228.6	4.92	14.76
EF3	[62 - 75]	232	29.09	23.28	736.3	548.6	15.96	63.84
EF4	[75 - 89]	57	52.55	34.84	997.9	804.7	52.44	262.2
EF5	[89 - 105]	9	71.95	58.95	1635.8	1920.2	117.70	706.2

Once the criteria for the research are defined (see ANNEX 1 of the Supplementary Materials for details), the events reported in the database are extracted and classified according to their intensity in the EF scale, starting from the rating given in the database reports, which use the Fujita scale or the TORRO scale (for whose equivalence with the EF scale categories reference to Maeden et al [27]. was made). An example of this can be found in Table S1 of the Supplementary Materials with reference to the case study reported in paragraph 3.

The difference between tornadoes intensity is not only the speed of the wind, but also the surface interested by the same: as the former increases, also the latter. Several studies have investigated the relationship between the intensity of the tornado and the length and width of its path [36,37]. Since no information about the path is available for each event extracted from the database, the mean values reported in Elsner et al [37]. were used to calculate an average impact surface for each *i*-th tornado intensity category. These surfaces are used for the calculation of the Destructive Potential Index (DPI). It is an index developed in Thompson et al [38]. and Doswell et al [39]., used for the comparison of different tornado outbreaks, but that can also be referred to a single tornado event, in this case, the "specific DPI" [40], DPI_{EFi}, is the tornado area (length times width), a_i, multiplied by the (E)F-scale plus 1.

$$DPI_{EFi} = a_i \cdot (EF_i + 1) \tag{1}$$

The Destructive Potential Index is obtained by summing the specific DPIs of the individual tornadoes that made up the outbreak. The DPIs computed for each category of the EF scale are reported in Table 1.

For each *i*-th degree of EF scale, the frequency of occurrence is estimated by the ratio of the number of recorded events to the survey period. To normalize the frequency with respect to the area from which the reports are extracted, and to take into account the different impact surface, which statistically affects the probability of being struck by the tornado (and the different destructive power of the same), a normalized frequency ([events/years]) of each *i*-th category of tornado is computed by multiplying the frequency of occurrence with the respective DPI and dividing it by the surface of the cell investigated, the calculation of which can be made using simple tools such as Google Maps.

$$Fr_{EFi} = \frac{number\ of\ events_{EFi}}{investigation\ period} \cdot \frac{DPI_{EFi}}{survey\ area} \tag{2}$$

2.2. Identification of target equipments and damage modes

A specific work dedicated to identify the equipment typically damaged in a seismic and flood event, the damaged modes and their characteristics, has been carried out in other papers [1,9,42], with the aim also to realize a QRA that integrates, as a further precursor event of an incidental scenario, the possible impact of a natural hazard. Based on historical analysis of past Na-Tech events, atmospheric tanks, pressurized tanks, large-caliber pipes, heat exchangers, columns, reactors, pumps, and smaller lines have been identified as the most exposed equipment to both earthquakes and floods. The results of the above mentioned QRA show that large atmospheric tanks and pressurized tanks contribute more to determining the major accident risk, as they are equipment with a capacity much higher than the other, underlining, however, also the significant contribution to the release of hazardous substances attributable to large diameter pipes.

The same conclusions can be drawn for Na-Tech triggered by extreme windy phenomena, such as tornadoes, in other publications [18,21,43], where it is evident that the most likely to suffer damage are storage equipment and process equipment. The same documents also contain information about the possible damage modes to which they may be subject: rupture of pipes and connections, fixed and floating roof damage, buckling, overturning, and puncturing damage (debris impact). Among these, the last three have been identified to be the most likely and the most critical from the point of view of the expected consequences, and therefore the most investigated [22,23].

In accordance with the results of the above-mentioned QRA and to follow the approach implemented in Marzo et al [5]. and Busini et al [8]. the analysis will only consider the vulnerability of atmospheric storage tanks and pressurized storage tanks, compared to the phenomena of buckling, overturning and debris impact.

2.3. Probability of equipment failure

The vulnerability assessment of storage tanks exposed to strong gusts of wind has been carried out in several studies, both through a qualitative approach [20], and by means of quantitative approaches that also allowed to produce fragility curves [22,23,44,45]. However, the results obtained are hardly universally applicable to all the tanks investigated, indeed the assignment of specific damage probability to a tank subject to the impact of a windy event of a given intensity is a problem of difficult resolution, since numerous are the parameters that contribute to its variability, both geometric (e.g., as the tank diameter, height, and thickness) and instance-specific (e.g., the filling level, the presence of anchorage or wind girder and the position in the plant layout).

However, for each of the three previously identified damage modes it is possible to pinpoint relations that assign specific wind speed values to specific damage probabilities. If such correlations are not available in the literature, threshold values of wind speed will be identified from time to time on the basis of historical analysis and structural technical considerations, and a dichotomous damage probability will be assigned, considering certain the damage (i.e., $DP = 1$) for events of higher intensity and impossible (i.e., $DP = 0$) for events of lower intensity.

Since the damage can occur as a result of any of the three mechanisms investigated, and due to tornadoes classified with any of the category of the Enhanced Fujita scale, each tank *k* can be assigned a total damage probability, indicated as *DP* and expressed in terms of [events/year], calculated according to eq. (3).

$$DP = \sum_{i=1}^{5} Fr_{EF_i} \cdot \left(OP_{EF_i} + BP_{EF_i} + DIP_{EF_i}\right) \tag{3}$$

Where OP_{EF_i}, BP_{EF_i}, DIP_{EF_i} are the overturning, buckling, and debris impact probability, and were assessed as described in paragraphs 2.3.1, 2.3.2, and 2.3.3. The relations used here are common to several other works devoted to the study of tank vulnerability to strong wind gusts [22,23,44,46].

Note that the term "*damage*" will be used, without referring to equipment "*failure*": this means that the structure of the tank itself is damaged because of the impact of the wind, but without specifying whether this damage is followed by an effective loss of functionality of the tank and a consequent loss of containment (LOC) of the stored material. The probability of LOC should be derived from the probability of damage and the probability of failure after damage [44]. However, the absence in the literature of enough studies obliges a precautionary approach in which the failure following the damage will be considered certain and consequently, both the damage and the failure probability will be considered equal. The extent of the loss of containment because of tank failure will be treated in section 2.4 dedicated to the identification of potential accident scenarios. Of course, this is a conservative approach that should be removed as soon as strong correlations between damage and LOC will be available.

2.3.1. Overturning

Key factors in determining the severity of the impact on tanks are the filling level, the presence of anchorages and the maintenance status of the structure, since in past disasters the damaged tanks were almost empty (i.e., full to less than 15% of their capacity), without anchors, or in vulnerable structural conditions [20]. These considerations apply even more to overturning. According to previous work, this is one of the least likely types of damage to occur, more typical for small tanks [47], and when it occurs the storage tank must be empty or partially empty

[23].

Here reference will be made to the API 650 standard [48], which establishes some stability criteria (overturning stability) for anchorage and unanchored vertical storage tanks subjected to strong winds. The standard states different relations to assess the tank overturning. The complete approach is extensively reported in ANNEX 2 of Supplementary Materials.

The analysis is repeated from time to time for every tank k, taking as reference wind speed corresponding to the upper limit for each EF category of tornado intensity, thus assigning to each category a probability for tank k to overturn equal to zero (i.e., $OP_{EF_i} = 0$) when the relation in ANNEX 2 of Supplementary Materials is satisfied, and equal to one (i.e., $OP_{EF_i} = 1$) when it is not.

For horizontal pressurized tanks, given the low center of gravity, a greater shell thickness than the atmospheric ones (i.e., a higher mass), and the strength of their anchorings, overturning is not considered likely, if not during events of extreme intensity. Based on these considerations a qualitative approach was followed, and a set of overturning probabilities varying with the tornado intensity was assigned. This equipment will be assigned an overturning probability equal to 0.4 for EF3 ranked tornadoes ($OP_{EF_3} = 0.4$), equal to 0.6 for EF4 ranked tornadoes ($OP_{EF_4} = 0.6$) and equal to 1 for EF5 ranked tornadoes ($OP_{EF_5} = 1$), while no possibility of overturning was evaluated for other events of lower intensity.

Of course, these parameters could be changed in the methodology once data on the probability of overturning is available in the literature. However, the influence of attributing these values was already evaluated in the sensitivity analysis performed downstream of the case study, as presented in paragraph 3.3.2.

2.3.2. Buckling

The "*buckling*" is the deformation, or the sudden change of shape, of a structural component, typically a metal shell, subjected to load. Thus, it is a typical damage mode involved during storms/tornado and flooding, affecting the upper section of storage tanks during storms and hurricanes, while buckling of the lower section is more likely due to floods [49].

Godoy [49] and Wang et al [44]. highlighted the main parameters capable of influencing the vulnerability to buckling of atmospheric vertical storage tanks, these are: tank design (i.e., height, diameter, and shell thickness), structural material properties (Young's modulus and Poisson's ratio), distribution (i.e., spacing, relative position and pattern) of tank groups and topographic effects (i.e., hills, containment dikes). Moreover, the presence of ring stiffeners (wind girder) may reduce the risk of tank deflections, as in past hurricane events, tanks with ring stiffeners did not exhibit buckling, even in areas where buckling damage was instead observed in unreinforced tanks [49].

However, also for buckling the most critical factor in determining the damage probability of the tank appears to be his filling level [22], since when a vessel is empty, the structure is at its lowest strength against buckling, and it is vulnerable to either wind or water pressure [18]. In this sense, specific studies have been conducted to identify the influence of the filling level of a tank on its probability of buckling, also to determine the minimum filling level necessary to prevent this damage mode [50].

Various logistic regression-based fragility models for wind-induced buckling are reported in literature [15,16,51], however the vulnerability curves produced are hardly applicable in general to all the atmospheric storage tanks, as they are strongly dependent on the great variability of the parameters that come into play, especially the tank height and diameter, the shell thickness, the filling level, and the presence of wind girders. The developing of fragility curves for all tanks potentially present in the analysis, which differ from each other by the characteristics mentioned above, is a very time-consuming activity that should be carried out only in a QRA, to be performed downstream this short-cut analysis, for installations where a not negligible risk is identified.

A more convenient approach is provided in the guidelines for the design of atmospheric storage tanks against external wind loads reported in several standards, such as the API 620 [52] and the API 650 [48]. According to these standards, shell buckling occurs when the pressure exerted by the wind load P_w at any point along the tank shell exceeds the tank resistance pressure P_r, which is the sum of the tank critical pressure P_{cr}, i.e., the maximum resistance pressure of the tank shell material, and the fluid pressure P_f exerted by the fluid stored in the tank.

The complete approach with the relations applied to compute the wind load P_w, the critical pressure P_{cr}, and the fluid pressure P_f is extensively reported in ANNEX 3 of Supplementary Materials.

As for the overturning, the analysis is repeated from time to time for every tank k, taking as reference wind speed that upper limit for each EF category of tornado intensity, thus assigning to each category a probability for tank k to buckle equal to zero (i.e., $BP_{EF_i} = 0$) when the relation in ANNEX 3 of Supplementary Materials is satisfied, and equal to one (i.e., $BP_{EF_i} = 1$) when it is not.

Buckling for pressurized vessels is not considered credible, given the high thickness of their shell, designed to withstand operating pressures of several bars. These equipments, therefore, will be assigned zero probability of buckling at any wind speed (i.e., $BP = 0$).

2.3.3. Debris impact

One common feature of a tornado is wind-generated debris, caused by wind speeds exceeding the threshold for lifting various elements into the air. Such wind-borne debris may have the potential to damage storage tanks, in a phenomenon also referred to as "puncturing damage" [21]. This is the most critical damage mode among those studied, because, while overturning and buckling can occur only at remarkably high wind speeds and under specific filling conditions, severe damage of this type can be already observed in tornadoes ranked as EF1 intensity.

Different models have been proposed to assess whether an object dragged by the wind carries enough force to cause possible damage, by comparing it to the resistance force of the tank. Nguyen et al [53]. developed a model based on the physical and mechanical characteristics of the debris and the target, given the angle of incidence. This method provides correlations to estimate the penetration depth of the debris after the impact and then compare it with the actual thickness of the target. However, in the present work a different approach will be applied and it is extensively reported in ANNEX 4 of Supplementary Materials. It involves the aerodynamic force on a static debris object in a wind field, the gravitational force, and the effect of its impact on a storage tank through the Probit function and the Johnson number J, a function often adopted in impact engineering for evaluating the severity of the impact. It has been used in other studies to assess damage probability to industrial equipment due to fragments thrown away by accidental explosion [54] and is defined as:

$$J = \frac{U^2 \; m_d}{\sigma_D \; t \; r_d^2} \tag{4}$$

Where U is the impact speed [m/s], σ_D is the dynamic yield stress (Pa), m_d and r_d are the debris mass [k] and the radius [m], and t is the shell thickness of the target [m].

The impact speed may be considered to coincide with the wind speed, applying a very conservative approach. Alternatively, a wind coefficient C_w, referring to the reduction of the impact speed compared to the wind speed, can be introduced. According to Lin et al. (2007) [55], the ratio of horizontal debris speed to wind gust speed, C_w, tends to increase with the distance, as the debris accelerates toward the wind speed, and it stabilizes in a range between 0.6 and 0.8. Consequently, the coefficient C_w, was introduced, assuming two different values. Firstly, a value of 0.6 was considered, then in the case study a sensitivity analysis was performed considering a value of 0.8.

A more extensive discussion of this coefficient is reported in ANNEX 4 of the Supplementary Materials.

2.4. Identification of potential accident scenarios

The consequences associated with the loss of containment of hazardous material differ according to the properties and quantity of substance released, which in turn depends on the size of the tank, the filling level, and the extent of damage. For large atmospheric tanks the failure is more typically due to the collapse of the structure, while for pressurized tanks the rupture of pipes and flanges or the perforation of the shell is the most probable, as reported in Campedel et al [9]., where, during the development of semi-empirical correlation between the intensity of the natural event and the probability of equipment failure, the severity of the damage was qualitatively classified into a number of discrete "damage states".

However, the lack of studies in the literature investigating the correlation between wind intensity and the likelihood of damage to equipment prevents an approach that is so thorough that it can diversify the intensity levels and the expected damage consequences. Therefore, in this work, only the worst hypothetical scenario will be prudentially considered, corresponding to the collapse of the tank, with loss of containment of the entire inventory.

An overview of the possible phenomena observed following the release is provided in many works [56,57], and it is also reported in Figure S3 of the Supplementary materials. In the phase of consequences modelling, for each incidental scenario (evaporating pool, pool fire, jet fire, flash fire, BLEVE, and physical explosion) it is possible to identify the physical phenomenon (heat radiation, overpressure, and fragment projection) that denotes its danger, as well as constitutes, for some of them, the escalation vector responsible for the propagation of the primary event to surrounding equipment ("secondary targets"), involving them in the accident, as will be treated in the following paragraph dedicated to the domino effect.

2.5. Assessment of domino effect

Tank damage, and ultimately its collapse, can occur either directly because of the impact of the natural phenomenon, or by domino effect because of the collapse of an adjacent tank. A domino event (also known in the literature as escalation or knock-on event) may be defined as an accident in which a primary event propagates to nearby equipment, triggering one or more secondary events.

Therefore, in the estimation of the probability of a tank collapse, both the direct effect of the wind, capable of causing buckling, overturning, or puncturing damage, and the damage due to domino effect triggered by adjacent tanks collapse shall be considered.

The domino effect analysis is quite complex and should consider all the possible scenarios listed above, also in consequence of each other, since usually, such events do not occur individually.

Different quantitative risk assessment methodologies for domino effect in NaTech events were proposed for scenarios triggered by lightning [58] and flooding [59]. Lan et al [60]. proposed a methodology for the identification of critical units based on a Natech-related domino evolution graphs that support the dynamic modeling of accident evolution considering the real-time interference of natural disasters.

These are quantitative approaches requiring considerable use of resources. Therefore, a simplified method for assessing the domino effect is proposed here. It requires to estimate for each tank j in the plant the safety distance d_s and to compare it with the actual distances d_{jk} between it and any other tank k. Following the work of Busini et al [8]., this approach leads to the construction of a n x n square matrix (where n indicates the number of tanks present in the plant), containing the P_{jk} values of the probability that the collapse of the tank j, due to the wind, involves the tank k, causing its collapse. For tank k the collapse by domino effect, as a result of the collapse of the tank j, will be considered certain (i.e., $P_{jk} = 1$) in case $d_{jk} < d_s$, vice versa will be considered impossible (i.e., $P_{jk} = 0$) in case $d_{jk} > d_s$.

Table 2
Escalation vector and threshold values for different primary accidental scenarios. These thresholds are those fixed in the Italian normative references (DM 15/5/96 [67] and DM 20/10/98 [68]) for damage to structures, and are therefore considered valid for any target equipment, both atmospheric and pressurized.

Accidental scenario	"Escalation vector"	Threshold value
Pool fire	Heat radiation	12,5 kW/m^2
Jet Fire	Heat radiation	12,5 kW/m^2
Fireball	Heat radiation	12,5 kW/m^2
BLEVE	Overpressure	30 kPa
	Fragment projection	600 m / 800 m
Physical explosion	Overpressure	30 kPa
	Fragment projection	600 m / 800 m
VCE	Overpressure	30 kPa
	Fragment projection	600 / 800 m

Since the number of d_{jk} distances to be calculated is equal to $n \times (n-1)$, for large plants with numerous storages, the use of a GIS software matched with a georeferenced map of the plant layout can greatly simplify the procedure.

Among the incidental scenarios mentioned in 2.4., only pool fire, jet fire, physical explosion, BLEVE, and VCE will be taken into account, not considering, therefore, flash fires that, even if characterized by intense heat radiation, due to their very short duration, are not considered able to structurally stress enough tanks to cause their collapse, as already assumed in other works [61]. Once the possible scenarios resulting from the collapse of a tank are identified, the safety distance d_s will correspond to the maximum between the safety distances d_{s_i} associated with any possible i-th accident scenario identified.

Numerous works have been dedicated to the identification of the escalation vector, the threshold values for the damage to nearby equipment, and the estimation of the safety distances able to safeguard the adjacent equipment from the domino effect [8,61–63]. For pool fires and jet fires it is the heat radiation to be identified as "escalation vector", while for physical explosions and VCEs are overpressure and fragments projection. Depending on the substance involved in the BLEVE, the physical phenomena able to cause escalation can be both overpressure and fragments projection, or heat radiation because of the fireball. For the latter, however, the same considerations about flashfire, concerning the short duration, may apply.

The threshold values for heat radiation vary in literature and technical standard from a minimum of 9.5 kW/m^2 for atmospheric equipment to a maximum of 50 kW/m^2 for pressurized equipment; while for the overpressure threshold the range varies from a minimum of 7 kPa to a maximum of 70 kPa [61,64,65], depending on the type of equipment and the "damage state" considered, highlighting how a greater shell thickness, characteristic of equipment operating under pressure, leads to greater resistance both to heat and pressure. The fragments projection is more difficult to analyze, which is yet among the more frequent causes of domino effect in industrial accidents: the escalation radius of this kind of phenomenon can be estimated as the maximum distance at which a fragment thrown from the explosion still has enough kinetic energy to penetrate the shell of other equipment. Several approaches were proposed in the literature for the assessment of fragment projection distances, depending on the initial explosion energy. In scenarios involving the burst of pressurized vessels, the projection distances are likely to be higher than 500 meters [66]. In Italy there are also normative references [67,68] for the evaluation of the effects of physical phenomena, which fix for damage to structures a threshold of 12.5 kW/m^2 for heat radiation and 0.3 bar for explosions, also indicating safety distances of 600 and 800 meters respectively for spherical and horizontal tanks for fragments projection in case of BLEVE, in accordance with the studies mentioned

Figure 2. Satellite photo of the case study plant [76].

above.

For each primary accident scenario, the "escalation vector" and the threshold values taken as reference in this paper are reported in Table 2.

Through consequence modeling software it is possible to estimate for fire and explosion scenarios the distances at which the threshold values for damage to an adjacent tank are reached and compare them with the actual distance between tanks. Alternatively, in the literature there are numerous approaches proposed for the evaluation of the effects of heat radiation generated by fires at certain distances [69,70], while for explosions there are traditional empirical methods for the overpressure prediction [71,72].

For a tank k to collapse by domino effect it is necessary that a first tank j collapses as a result of the wind interaction (such damage probability DP_j is estimated as indicated at 2.3), and that it is involved in the consequences of its collapse, collapsing in turn (this dichotomous probability P_{jk} is determined by the comparison between actual distances d_{jk} and safety distances d_s). Since both events must occur in succession, the probability for the tank k to collapse by domino effect can be estimated using the definition of conditional probability, by the product between DP_j and P_{jk}. A tank k can collapse by direct effect of the wind or due to domino effect: the overall probability that the tank k will collapse due to either of the two causes, called $\overline{DP}_k$ and expressed in [events/year], can be represented as the union of the two probabilities. From probability theory, the union of these two events, not mutually exclusive, is calculated as complementary to one of the probability of not collapsing for any reason [8], as expressed in equation (5):

$$\overline{DP}_k = 1 - \prod_{j=1}^{n} \left(1 - DP_j \times P_{jk}\right) \tag{5}$$

Where n is the number of tanks in the facility.

2.6. Analytic Hierarchy Process (AHP)

The probability of a tank collapsing is not alone indicative of the risk level associated with the event, in fact, the expected consequences, which vary according to the properties and quantities of substance released, contribute to defining it too. Making a comparison between two possible scenarios is not easy: for example, between the release of 100 tons of LPG or 10000 tons of a generic liquid hydrocarbon, which should be considered worse?

To conduct a simplified evaluation of the Na-Tech risk level related to extreme storm events, considering various scenarios (e.g., a process plant at a specific location) and accounting for multiple parameters - often challenging to compare due to differing units of measurement [73] - this study proposes a method based on the implementation of the Analytical Hierarchy Process (AHP).

The AHP is a multi-criteria decision tool to account for the different and often incommensurable effects of various parameters [24] and, if applied to the risk analysis, allows the analyst to respond to a simple question: "Is the Na-Tech risk level associated with process plant A (or to item A) larger than the risk level associated with process plant B (or to item B)"? Where variables A and B can be whether two different plants (or items) located in two different positions, or the same plant (or item) with different mitigation measures implemented [8].

All details concerning the development of AHP will not be discussed here, as they are extensively reported in other papers dealing with the development of short-cut procedure for assessing earthquake-related and flood-related Na-Tech risk [5,8]. Here it suffices to mention that this method allows for a rational choice between alternatives on the basis of binary comparisons (i.e., comparisons involving only two elements at a time), expressed as qualitative judgments on an arbitrary scale, eventually leading to the attribution of performance indices, named for this application: Key Hazard Indicators (KHIs).

Since in Na-Tech accidents, the main consequences are broadly due to three phenomena; fires, explosions, and toxic dispersions, Busini et al [8]. has developed three different hierarchies (reported in Figure S4 of the Supplementary materials), considering the properties identified, compared, and ranked as relevant in determining the danger of a substance such as IDLH and vapour pressure for toxic compounds, or the state of aggregation, the values of combustion enthalpy and flash point for flammable and explosive compounds. The storage pressure shall also be considered for the latter. From the combination of these parameters 8 alternatives ($\overline{M}_{Fn}$) for flammable substances (F), 8 alternatives ($\overline{M}_{Tn}$) for toxic (T) ones, and 5 alternatives ($\overline{M}_{En}$) for explosives (E) are identified and each of them is attributed a "path factor" (Φ) on 0-1 scale.

Figure 2

For each tank k, according to the hazard classification of the material

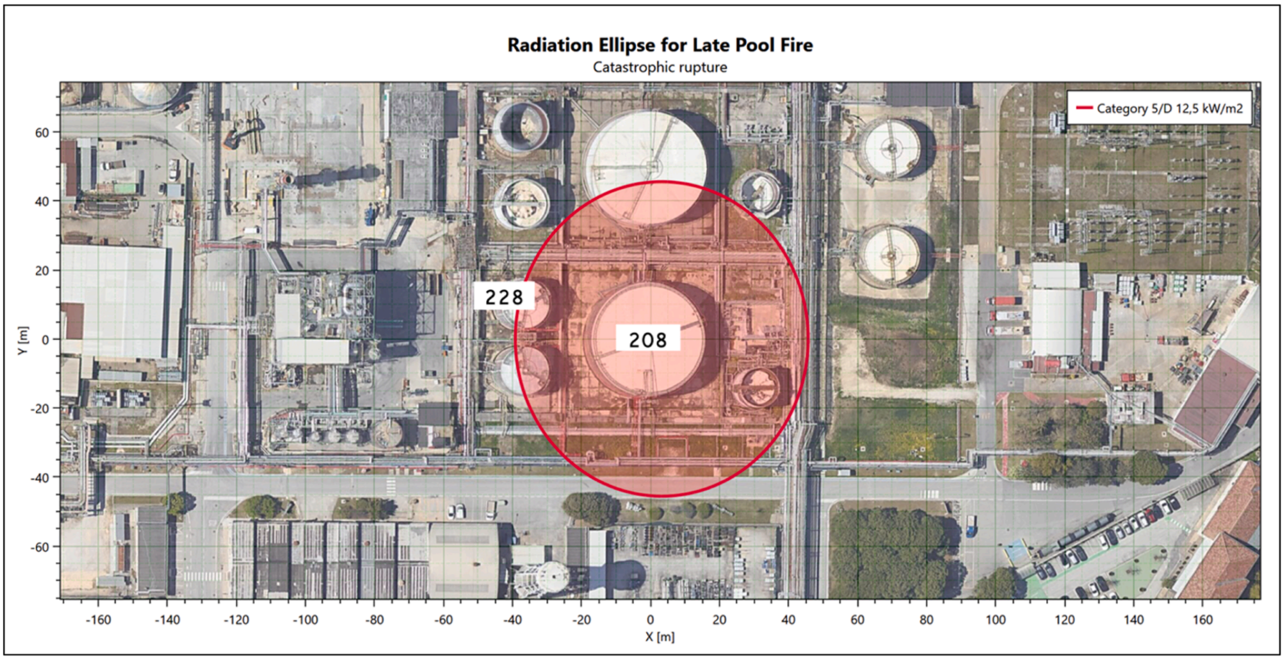

Figure 3. Threat area for heat radiation with a threshold of 12,5 kW/m^2 due to a pool fire generated by the collapse of the tank 209.

it contains, a "relative mass percentage" ($M_{\%k}$) is evaluated as the ratio of the stored mass to its limit set by article 8 of the Seveso III European Directive (Directive 2012/18/EU) [74], which define the maximum quantities of the substance that can be stored in an installation without requiring a quantitative risk assessment, as described in eq. (6).

$$M_{\%k} = \frac{mass\ of\ substance\ i\ stored\ in\ tank\ k}{Seveso\ III\ treshold\ for\ substance\ i} \tag{6}$$

For each tank k, a reference mass ($\overline{M}_k$), expected to be released in case of tornado, can be computed from its overall damage probability ($\overline{DP}_k$) and its relative mass percentage $M_{\%k}$ as:

$$\overline{M}_k = M_{\%k}\ \overline{DP}_k \tag{7}$$

To the collapse of each tank k is then attributed three distinct indices, KHI_{k_F}, KHI_{k_T}, and KHI_{k_E}, for fire, toxic dispersion, and explosion, respectively. To do that, the stored material must be classified: this can be done according to the European Chemicals Bureau (Council Directive 1272/2008/EEC), which has classified substances in various classes depending on their hazardous properties. Toxic substances (classified as GHS05, GHS06, GHS07, GHS08 GHS09) will feed the KHI_T hierarchy, while flammable substances (classified as GHS02) and pressurized gaseous substances (classified as GHS04) will feed the KHI_F and KHI_E hierarchy [8]. Each index is computed as the product between the reference mass ($\overline{M}_k$) and the "path factor" of the relative hierarchy:

$$KHI_{k_h} = \overline{M}_k\ \Phi_h \tag{8}$$

Where the subscript h indicates the hierarchy (h=F, T, E) considered. More than one h can be defined for each tank k depending on the substances stored, based on its classification. By means of a summatory of the KHI_{k_h} associated to every tank k, it is then possible to assign three global indices, KHI_F, KHI_T and KHI_E, to the plant, as shown in eq. (9).

$$KHI_h = \sum_{k=1}^{n} KHI_{k_h} \tag{9}$$

Where n is the number of tanks in the plant and h indicates the hierarchy (h=F, T, E) considered. These KHIs are therefore constructed in such a way as to be sensitive to the main variables identified as influencing risk, namely: the local frequency and intensity of stormy events; the vulnerability of storage to the strong wind and to the domino effect; the quantity of the substances stored and their danger properties (toxicity, flammability, explosive potential).

Considering a 3D KHIs Euclidean space, each point on it, identified by the three values, KHI_F, KHI_T and KHI_E, represents the overall risk level of the plant, to which it is possible to associate a global risk index (KHI_G), corresponding to the vector starting from the origin up to that point [8]. Consequently, the value of KHI_G, equal to the length of the vector, can be calculated as the square root of the sum of the three squared KHIs:

$$KHI_G = \sqrt{KHI_F^2 + KHI_T^2 + KHI_E^2} \tag{10}$$

This index can assume values that can be grouped into three intervals to assign a Na-Tech risk level in respect to tornadoes. Following the approach used in Busini et al [8]. a possible classification is shown below:

- low risk level: $KHI_G < 10^{-2}$
- medium risk level: $10^2 < KHI_G < 10^{-1}$
- high risk level: $KHI_G > 10^{-1}$

Highly rated plants require further Na-Tech risk analysis, while lowly rated plants do not. For medium-ranked plants, the situation can be judged as neither negligible nor unacceptable. This is a sort of ALARP (as low as reasonably practicable) region [75]: in this case the decision on how much further the risk assessment must be conducted is up to the analyst and must be decided on a case-by-case basis.

3. Results and discussion

3.1. Application for a case study

The developed methodology was applied to an Italian Seveso petrochemical plant with many items potentially subject to Na-Tech risk (Figure 3), initially located in the Veneto region, since, as a result of historical analysis, Veneto appears to be the Italian region most susceptible to tornadoes.

The layout of the case study is reported in Figure S5 of the

Table 3
Results of the historical analysis.

Classification	Number of recordered events	Fr_{EFi}
EF1	15	7.16×10^{-5}
EF2	5	1.51×10^{-4}
EF3	1	1.31×10^{-4}
EF4	2	1.08×10^{-3}
EF5	0	0

Table 4
Characteristics of the atmospheric storage tank 228.

	Parameter	Value	Unit
ID	Tank identification number	228	-
-	Substance	Gas oil	-
ρ_s	Substance density (@ 15°C)	835	kg/m^3
P_V	Substance vapour tension (@ 40°C)	0.4	*kPa*
C	Capacity	1532	m^3
D	Diameter	14	*m*
H	Height	10.4	*m*
t^*	Shell Thickness	4.8	*mm*
t_R^{**}	Roof Thickness	5	*mm*
t_B^{**}	Base Thickness	6	*mm*
DL	Shell and base mass	24.5	*ton*
DLR	Roof mass	6	*ton*
FL	Filling level	10	%
-	Shell material	Stainless steel AISI 302	-
σ_D	Ultimate Tensile strength σ_D	620	*MPa*
ρ_{ss}	Steel density	7850	kg/m^3
E	Young Module	193	*GPa*
υ	Poisson's ratio	0.231	-

Since no information about the plate thickness are available in the open literature, reference was made to the API standards [48,52]: * The API 620 standard states a minimum nominal shell thickness which varies according to the tank diameter (Table 5.6). ** The API 650 standard states that all roof plates and bottom plates shall have a minimum nominal thickness of 5 mm (paragraph 5.10.2.2) and 6 mm (paragraph J.3.2.1) respectively.

Supplementary Materials, while Table S3 of Supplementary Materials summarizes the characteristic (ID number, diameter, height, shell thickness, capacity, containment dike area, containment dike height, stored substances, and filling level) of the 96 atmospheric storage tanks and the 16 pressurized vessels analyzed.

The territorial characterization was carried out through the ESWD considering a survey area of 9020 km^2, from the 45th to the 46th parallel north and from the 12th to the 13th meridian east, since the plant falls inside the cell number 12 (see map in Figure S1 of the Supplementary materials), and a survey period of 54 years, from 01/01/1970 to 18/04/2024. The number of the recordered events, their classification, and the normalized frequencies are reported in Table 3 (a more extensive report of the events extracted from the database is shown in Table S1 of the Supplementary materials).

For each tank, through the approaches and the correlations reported in 2.3., a probability of failure was assigned at every upper limit wind speed of the EF scale. For the sake of simplicity, here the whole procedure is presented for an example tank, namely tank 228, which characteristics are reported in Table 4. The full vulnerability analysis of tank 228 is reported in ANNEX 5 of Supplementary Materials.

Starting from the overturning analysis, based on assumptions made at 2.3.1, in the first place only slender tanks (with ratio height/diameter at least equal to 0.5) with filling level less than 50% were considered likely to overturn and therefore analyzed. Since no information about anchorages was available, the tanks resulting from this first selection were analyzed first as if they were unanchored, then, when the overturning risk was found even for winds lower than EF2, these were considered required for anchorages (whereas the API standard provides design criteria for anchorages by reference to a wind at 190 km/h). For these tanks, and for the ones dedicated to the storage of gasoline or kerosine, substances with high vapour pressure, the anchorages become necessary, and the analysis is repeated considering them as anchored.

For the analysis of the buckling vulnerability equation reported in ANNEX 3 of Supplementary Material was applied. For the wind load calculation, reference was made to the European Standards (Eurocode 1: Actions on structures) [77], applicable for cylindrical structures.

The vulnerability to the impact of debris carried by a wind of a given speed depends on the thickness of the shell and the mechanical properties of its material. The considerations about the calculation of Johnson's number are reported in ANNEX 5 of the Supplementary materials. As regards the wind coefficient C_w, which refers to the reduction of the debris speed compared to the wind speed, in the base case it was assumed equal to 0.6. A more extensive discussion on this coefficient is reported in ANNEX 4 of the Supplementary Materials and the variation of the results due to the changing of its value is reported in paragraph 3.2. dedicated to the sensitivity analysis to the parameters.

The results of vulnerability analysis of tank 228 are reported in Table 5.

Through the frequencies given in Table 3 and the damage probabilities shown in Table 5, tank 228 can be assigned, according to equation (3), a total damage probability (*DP*) due to the direct effect of the wind equal to 1.35×10^{-3}. The total damage probabilities for all the other tanks are reported in Table S5 of the Supplementary materials.

The next step concerns the evaluation of the domino effect: for each tank, the possible scenarios reported in 2.4. were considered. For atmospheric tanks pool fire was evaluated as the most likely event to lead to an escalation, while for pressurized tanks both overpressure and fragment projection due to BLEVE and heat radiation due to fireball and jet fire were considered. For the former, the size of the pool fire was deemed to coincide with the area of the containment dike, and the safety distance d_s (i.e., the distance at which the heat radiation threshold value given in Table 2 is reached) was evaluated by PHAST (considering a 5/D Pasquill Stability Class) and compared with the actual distances between the tanks, d_{jk}. For pressurized tanks, the danger zone due to jet fires is smaller than that due to other phenomena. The safety distance for the threshold of 0.3 bar of overpressure due to the shock wave generated by BLEVEs can be evaluated again by PHAST or by the correlations presented in Cozzani et al [62]., finding with both approaches values in the order of 120 meters. This value is lower than the 800 meters recommended by the Italian regulations for the protection from fragments

Table 5
Vulnerability analysis results for the atmospheric storage tank 228. As reported in ANNEX 2 of Supplementary Materials, the API 650 standard [48] establishes 2 conditions that have to be both satisfied in order to avoid the tank overturning.

Wind speed			Overturning						Buckling			Debris impact	
category	*km/h*	*m/s*	P_w [*kPa*]	F_w [*kN*]	M_w [*kN m*]	Condition 1	Condition 2	*OP*	P_w [*Pa*]	Condition	*BP*	*J*	*DIP*
EF1	177	49	1.19	197	8.98×10^2	*satisfied*	*satisfied*	*0*	2184	*satisfied*	0	0.0084	2.67%
EF2	217	60	1.93	322	1.46×10^3	*satisfied*	*satisfied*	*0*	3306	*satisfied*	0	0.0189	4.55%
EF3	266	74	2.91	483	2.20×10^3	*unsatisfied*	*satisfied*	*1*	5076	*satisfied*	0	0.0423	7.44%
EF4	322	89	4.26	708	3.22×10^3	*unsatisfied*	*satisfied*	*1*	7400	*satisfied*	0	0.0913	11.24%
EF5	512	142	10.76	1791	8.15×10^3	*unsatisfied*	*unsatisfied*	*1*	19190	*unsatisfied*	1	0.5806	25.23%

Table 6
Results of the tornado-related Na-Tech risk assessment for tank 228 of the case study plant.

Inventory [ton]	Sesevo Threshold [ton]	Relative mass percentage $M_{\%228}$	Overall damage probability $\overline{DP}$	Reference mass $\overline{M}_{228}$	Φ_F	Φ_T	Φ_E	KHI_F	KHI_T	KHI_E
128	25 000	5.12×10^{-3}	3.02×10^{-3}	1.55×10^{-5}	0.1089	0.0194	0.0100	1.68×10^{-6}	3.00×10^{-7}	1.54×10^{-7}

Table 7
Results of the tornado-related Na-Tech risk assessment for the case-study plant, considering it as it was located in seven different sites. The classification reported in 2.6. allows to assign a specific risk level to each site: low risk level (green); medium risk level (yellow); high risk level (red).

Site	Survey area [km^2]	Survey period [years]	Recordered tornado events					KHI_F	KHI_T	KHI_E	KHI_G
			EF1	EF2	EF3	EF4	EF5				
Oklahoma City, OK	14 000	72	189	110	38	15	4	4.44×10^{-1}	1.28×10^{-1}	3.11×10^{-1}	5.57×10^{-1}
Tallulah, LA	14 000	72	154	70	23	4	3	2.56×10^{-1}	7.38×10^{-2}	1.79×10^{-1}	3.21×10^{-1}
Marghera (VE)	9020	54	15	5	1	2	0	5.13×10^{-2}	1.48×10^{-2}	3.62×10^{-2}	6.46×10^{-2}
Minerbio (BO)	9030	54	5	3	4	0	0	1.55×10^{-2}	4.47×10^{-3}	1.09×10^{-2}	1.95×10^{-2}
Brindisi	18940	54	20	4	3	0	0	5.63×10^{-3}	1.62×10^{-3}	3.95×10^{-3}	7.07×10^{-3}
Livorno	9257	54	12	4	0	0	0	2.85×10^{-4}	7.51×10^{-5}	1.56×10^{-4}	3.34×10^{-4}
Roma	18574	54	28	6	0	0	0	2.38×10^{-4}	6.27×10^{-5}	1.30×10^{-4}	2.79×10^{-4}
Bussi sul Tirino (PE)	10380	54	1	1	0	0	0	5.46×10^{-5}	1.44×10^{-5}	2.99×10^{-5}	6.39×10^{-5}
Milazzo (ME)	40000	54	11	2	0	0	0	3.88×10^{-5}	1.02×10^{-5}	2.12×10^{-5}	4.54×10^{-5}

projection, however the high degree of congestion, due to the buildings and other equipment located to the south and west of the pressurized tanks constitute a sort of shield from the possible impact of debris thrown by the explosion for most of the storage tanks in the plant, while a threat radius of 120 meters is sufficient to include most of the tanks located to the north and east of the LPG vessels. For that reason, the safety distance needed to protect against the blast wave overpressure was taken as a reference. However, this is a case-specific assessment, which may vary depending on the layout of the plant.

Tank 228 was found to be potentially affected by the collapse of tanks 208, 209, 227 and 229. As an example, Figure 4 shows the result of the simulation of the threat area due to a pool fire generated by the collapse of the tank 208. All the information about the containment dike sizes and the safety distances of each tank of the whole plant, computed through PHAST, is reported in Table S3 of Supplementary Materials.

Through the equation (5), every tank *k* can be assigned an overall damage probability, which considers both the direct effects of the wind (buckling, overturning and puncturing damage) and the domino effect due to the collapse of an adjacent tank *j*. After having also calculated the damage probabilities of the 4 tanks close to the tank 228 under examination, and knowing its one, it is possible to estimate its overall damage probability, $\overline{DP}_{228}$, which is equal to 3.02×10^{-3}.

Finally, the inventory and the properties of the stored material need to be considered. On the basis of the physical properties of gas oil (reported in Table S6 of Supplementary materials), according to the AHP developed in Busini et al [8]., the following alternatives can be assigned: $\overline{M}_{F3}$ for the fire hierarchy, $\overline{M}_{T7}$ for the toxic hierarchy, and $\overline{M}_{E3}$ for the explosion hierarchy. The relative "path factors" Φ_h are reported in Table 6, together with the Seveso threshold for the stored substance, the relative mass percentage ($M_{\%228}$), the reference mass ($\overline{M}_{228}$) and the Key Hazard Indicators.

The whole procedure was applied to all the 112 tanks, that is three specific KHIs were evaluated for all of them (reported in Table S8 of the Supplementary materials), and through the equation (10), a global Key Hazard Indicator, KHI_G, equal to 6.46×10^{-2} can be assigned to the entire plant. It must be mentioned, as a sensitivity analysis that, if the safety distance of 800 m for the protection against the fragment projection had been considered for the pressurized tanks, KHI_G would not have undergone drastic changes, increasing to a value of 8.67×10^{-2}. In both cases, following the classification reported in 2.6., the results correspond to a medium risk level situation (i.e., ALARP).

3.2. Sensitivity analysis

3.2.1. Sensitivity analysis to the location

To better contextualize and evaluate the results, the methodology was applied again considering the same plant located in other eight different sites, six Italian (Minerbio (BO), Rome, Livorno, Brindisi, Bussi sul Tirino (PE) and Milazzo (ME)) and two in the United States (Oklahoma City, Oklahoma and Tallulah, Louisiana). For American locations, reference was made to the "tornado tracks tool" realized by the Midwestern Regional Climate Center using data provided by the Storm Prediction Center (SPC), a US government agency that is part of the National Oceanic and Atmospheric Administration (NOAA).

The results reported in Table 7 show how Veneto region appears to be indeed the Italian location most prone to tornado impact, with a KHI_G of at least an order of magnitude higher than that attributable to any other Italian territory, but lower than that associated with the American sites located in the so-called "Tornado Halley", a central region of the United States, which entirely includes states like Oklahoma, Kansas, Arkansas, Missouri and Iowa, and partially others like Louisiana, Texas and Colorado, characterized by one of the higher frequency of tornado formation in the world.

3.2.2. Sensitivity analysis to the parameters

As already highlighted in paragraph 2.3 the scarcity of studies on the interactions between strong wind gusts and industrial structures, and in particular with tanks, lead to the introduction of some simplifications and assumptions in this methodology. Most of them are related to the damage probability assessment, especially referring to the debris impact and pressurized vessel overturning scenarios. Therefore, the case study was at first analyzed by applying a less conservative approach, then a sensitivity analysis was performed with the aim to evaluate the validity of the method and the consistency of the results it returned when certain parameters are changed.

The first parameter analyzed during this sensitivity is the wind coefficient C_w introduced during the puncturing damage assessment to take into account the reduction of the impact speed of the debris compared to the wind speed. According to Lin et al. (2007), this coefficient can vary in a range between 0.6 and 0.8.

Consequently, both the limit values of C_w, i.e., 0.6 and 0.8, were considered during the sensitivity analysis.

The second assumption made in the methodology concerns the overturning probability. While for atmospheric storage tanks reference

Table 8
Values assigned for the parameter set.

Parameter	PARAMETER SET A	PARAMETER SET B
C_w	0.6	0.8
OP_{EF_1}	0	0
OP_{EF_2}	0	0
OP_{EF_3}	0.4	0.5
OP_{EF_4}	0.6	0.75
OP_{EF_5}	1	1

can be made to the stability criteria established by the API 650 standard [48], no specific approach regarding the analysis of pressurized vessels is available in the literature. In this paper, a qualitative approach was thus followed and a set of overturning probabilities varying with the tornado intensity was assigned. As already reported in paragraph 2.3.1, given the low center of gravity of horizontal pressurized tanks, a greater shell thickness compared to the atmospheric ones (i.e., a higher mass), and the strength of their supports, overturning is not considered likely, if not during events of extreme intensity, starting from EF3 ranked tornados.

Two different set of overturning probability were considered, one less conservative (already reported in paragraph 2.3.1. and applied in the case study presented above) and other more. These are reported in Table 8.

By combining the uncertainties of these parameters, two limit scenarios can be produced. The first and least conservative one, named CASE A is the one already analyzed before, considering a lower C_w coefficient, equal to 0.6, and a lower values of overturning probabilities for pressurized vessels. The second one, named CASE B, is the most conservative one as it assumes a higher C_w value, equal to 0.8, and sets the highest overturning probabilities for horizontal pressurized tanks.

The two set of parameters applied in CASE A and CASE B are reported in Table 8, while Table 9 shows a comparison between the results of the Na-Tech risk assessment obtained by applying the methodology to the same nine sites presented in the sensitivity analysis to the location and considering one or the other set of parameters.

The variation in the values assigned to the parameters under evaluation seems to not have a significant impact on the results as the sensitivity analysis showed no change in the risk level classification attributed to each location. Considering that the sensitivity analysis using extreme parameters led to the same classification, not all combinations of the analyzed parameters were examined.

The methodology proved to be valid, returning consistent results, and not too much influenced by the inherent uncertainties of vulnerability analysis.

4. Conclusions

Na-Tech events resulting from the impact of tornadoes on industrial sites represent a potential initial cause of direct and indirect releases of hazardous materials, and therefore their occurrence must be considered in risk analysis.

The purpose of this study was to fill a gap in NaTech risk assessment, providing a reference methodology for the assessment of industrial risks induced by tornadoes through the definition of KPIs that take into account the main variables identified as influencing risk, such as the local frequency and intensity of stormy events; the vulnerability of storages to strong wind and domino effects; the amount of stored materials and their hazardous properties (i.e., toxicity, flammability, and explosive potential). The analytic hierarchy process (AHP) was used to define these indices, thus developing a methodology that requires few resources and little information on both the expected impact frequency of a tornado and the plant, suitable at any stage of the life of a plant (i.e., from the early design stage to an already existing plant).

Finally, the developed methodology was applied to a case study, a refinery located in the Italian region most prone to tornados impact, obtaining a global risk index, KHI_G, according to which the plant can be classified as medium risk. To better evaluate the results, a sensitivity analysis to the location was performed, applying the methodology again by considering the same plant located in other sites, both in different Italian regions, obtaining low and negligible risk levels, and in those American territories characterized by the higher frequency of tornado formation in the world, finding for these cases KHI_Gs of at least an order of magnitude higher than that attributable to any other Italian territory, and therefore classifiable as high risk.

The results were in accordance with the expected statistical incidence, this means that, although some assumptions were made, the methodology proved to be valid and effective in identifying the most critical situations that will require further and quantitative analysis.

In fact, due to the scarcity of studies on the interactions between strong wind gusts and industrial structures, this methodology has had to make some simplifications and assumptions. Most of them are related to the damage probability assessment and involve all three different damage modes investigated. For example, in the event characterization, it was assumed the peak wind speed of each category of the EF scale as the reference wind speed for each category, even if it is not expected the whole investigated area experience these speeds. Of course, this is a conservative approach, and it should be removed, along with all the conservative assumption and simplifications introduced, as soon as more studies about tornados and their interactions with storage tanks, and in general with industrial facilities, are available, and the strength of the proposed methodology is that it can include them without changing its structure.

A sensitivity analysis to the parameters was also performed to evaluate the validity of the method. It proved to be effective as the variation in the values assigned to the parameters under evaluation do not have a significant impact on the results. Therefore, the methodology proved to be valid, returning consistent results, and not too much influenced by the inherent uncertainties of the vulnerability analysis.

The methodology developed is generally applicable to any region of the world once the statistical data on the natural event are available and could also be extended to include other assets present in the plant when

Table 9
Results of the sensitivity analysis to the parameters.

Site	PARAMETER SET A				PARAMETER SET B			
	KHI_F	KHI_T	KHI_E	KHI_G	KHI_F	KHI_T	KHI_E	KHI_G
Oklahoma City, OK	4.44×10^{-1}	1.28×10^{-1}	3.11×10^{-1}	5.57×10^{-1}	5.91×10^{-1}	1.68×10^{-1}	4.01×10^{-1}	7.34×10^{-1}
Tallulah, LA	2.56×10^{-1}	7.38×10^{-2}	1.79×10^{-1}	3.21×10^{-1}	3.35×10^{-1}	9.51×10^{-2}	2.26×10^{-1}	4.15×10^{-1}
Marghera (VE)	5.13×10^{-2}	1.48×10^{-2}	3.62×10^{-2}	6.46×10^{-2}	7.46×10^{-2}	2.13×10^{-2}	5.13×10^{-2}	9.30×10^{-2}
Minerbio (BO)	1.55×10^{-2}	4.47×10^{-3}	1.09×10^{-2}	1.95×10^{-2}	2.32×10^{-2}	6.60×10^{-3}	1.58×10^{-2}	2.88×10^{-2}
Brindisi	5.63×10^{-3}	1.62×10^{-3}	3.95×10^{-3}	7.07×10^{-3}	5.96×10^{-3}	1.69×10^{-3}	4.01×10^{-3}	7.38×10^{-3}
Livorno	2.85×10^{-4}	7.51×10^{-5}	1.56×10^{-4}	3.34×10^{-4}	1.06×10^{-4}	2.80×10^{-4}	5.90×10^{-4}	1.24×10^{-3}
Roma	2.38×10^{-4}	6.27×10^{-5}	1.30×10^{-4}	2.79×10^{-4}	8.88×10^{-4}	2.36×10^{-4}	4.96×10^{-4}	1.04×10^{-3}
Bussi sul Tirino (PE)	5.46×10^{-5}	1.44×10^{-5}	2.99×10^{-5}	6.39×10^{-5}	2.00×10^{-4}	5.31×10^{-5}	1.12×10^{-4}	2.35×10^{-4}
Milazzo (ME)	3.88×10^{-5}	1.02×10^{-5}	2.12×10^{-5}	4.54×10^{-5}	1.45×10^{-4}	3.85×10^{-5}	8.09×10^{-5}	1.71×10^{-4}

studies on the interaction between strong gusts of wind and industrial facilities will produce relations and fragility curves also related to equipment other than storage tanks.

CRediT authorship contribution statement

Fabrizio Santamato: Writing – original draft, Validation, Methodology, Investigation. **Valentina Busini:** Writing – review & editing, Supervision, Methodology, Data curation, 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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ress.2025.111419.

Data availability

Data will be made available on request.

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