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Definition of a short-cut methodology for assessing earthquake-related Na-Tech risk

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ABSTRACT

Na-Tech (Natural and Technological) refers to industrial accidents triggered by natural events such as storms, earthquakes, flooding, and lightning. Herein, a qualitative methodology for the initial assessment of earthquake Na-Tech risk has been developed as a screening tool to identify which situations require a much more expensive Quantitative Risk Analysis (QRA). The proposed methodology, through suitable Key Hazard Indicators (KHIs), identifies the Na-Tech risk level associated with a given situation (i.e., a process plant located in a given territory), using the Analytical Hierarchy Process as a multi-criteria decision tool for the evaluation of such KHIs. The developed methodology was validated by comparing its computational results with QRA results that involved Na-Tech events previously presented in literature.

1. Introduction

Natural disasters may be powerful and prominent mechanisms of direct or indirect release of hazardous material (Hazmat) [1].

If industrial sites are located in naturally hazard-prone areas, technological accidents may be triggered by natural events, which could generate the so-called Na-Tech (Natural and Technological) events and may modify as well as increase the impact and overall damage in surrounding areas [2]. However, the term Na-Tech has been applied more broadly to other types of technological accidents and to natural events that may not be considered a disaster but that nonetheless trigger technological accidents (e.g., a winter storm that strikes a power line, which triggers a power outage) [3].

There is a wide range of literature on natural disasters and hazardous material accidents, but it is only in recent years that they have been treated as related events. Thus, Na-Tech events have begun to receive a significant amount of attention. Nevertheless, there is scarce information available on the interactions between natural disasters and simultaneous technological accidents and studies in this field have not been carried out extensively yet.

Many reviews on Na-Tech events spanning over 30 years have been written by several researchers [4–7]. Additionally, natural disasters have increased both in frequency and economic losses around the world [1]; therefore, there is increasing public awareness and interest from the scientific community. This increase in Na-Tech disasters is in part due to the fact that there are more people, industrial facilities, and infrastructure in large urban areas. Recent examples of Na-Tech events are reported in the literature [8–11], but only a few papers discuss approaches and methodologies necessary to face the problems they cause [2,10,12–14].

The most powerful tool to evaluate the impact that a natural event may have on industrial facilities is an extension of the classical Quantitative Risk Analysis (QRA) approach to situations wherein an accident is triggered by a natural event, which can enable both events to be addressed as a single one [15–18]. A limitation of QRA is that it requires a lot of resources in terms of time and expertise. A simple model that is easy to handle and capable of taking into account the most important phenomena that occur in a Na-Tech event, as well as describing them in terms of easily accessible data, should be useful for screening purposes (i.e., for deciding when it is worthwhile to conduct a QRA). Thus, a short-cut methodology for the assessment of industrial risks induced by earthquakes has been developed and validated by a comparison with available results from more detailed QRA.

2. Methodology

A screening procedure should be easy to apply and should require a small amount of resources and information. It should also summarize, through suitable Key Hazard Indicators (KHIs), the Na-Tech risk level associated with a given situation (i.e., a process plant located at a given position). The aim of such a screening procedure is to answer a simple question: "Is the Na-Tech risk level associated with process plant A (or to item A) larger than the risk

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Table 1
Saaty semantic scale for a pair-wise comparison [20].

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over the other
5	Strong importance	Experience and judgment strongly favor one activity over the other
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

level associated with process plant B (or to item B)"? Variables A and B can be two different plants or items located in two different positions or the same plant or item with different mitigation measures implemented. Unfortunately, answering this question requires simultaneous comparisons between a large number of different parameters, ranging from the types of hazardous substances present in the plant to the intensity of the external natural force, each of which have different units of measurement [19].

Thus, the need for specific methods to compare various risks is necessary to evaluate different risk levels corresponding to different individual risks using similar units. Therefore, it is necessary to develop a short-cut multi-risk methodology for the comparison and integration of natural hazards and industrial risk using suitable indexes. This requires the use of a multi-criteria decision method to account for the different and often incommensurable effects of various parameters. Among the various approaches available, the Analytical Hierarchy Process, AHP [20], is a method that can support decision making by establishing alternatives within a framework of multi-weighted criteria; its use has already been proposed in the context of Na-Tech risk analysis [21]. 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. Such comparisons are expressed as qualitative judgments that can be made quantitative through the semantic scale of Saaty, summarized in Table 1.

To use this method, the main elements that can influence the vulnerability of the plant with respect to earthquakes must first be identified. Such elements, while covering all the relevant aspects, should be few and easy to evaluate; once such elements are identified, hierarchies must be established to represent different possible events, which may allow an array of binary comparisons between elements belonging to the same level (by employing engineering judgments and using the scale of Saaty). Simple algebraic manipulations of these binary comparisons determine the weights for the various branches of the hierarchy [20].

Hierarchies are structured with the goal at the top (in this case it is the KHI) with different branches (structured at different levels) that represent a breakdown into sub-goals. Considering that this method is used to compare incommensurable elements, the rule used to define which elements could stay on the same level of the hierarchy is that they should respond to the same question. At the bottom of the hierarchy there are the alternatives that characterize the given plant with respect to the Na-Tech effects on people.

When considering earthquake related Na-Tech accidents, the consequences are broadly related to three main phenomena: fires, explosions, and toxic dispersions. As a consequence, three different hierarchies have been developed for Na-Tech accidents leading to

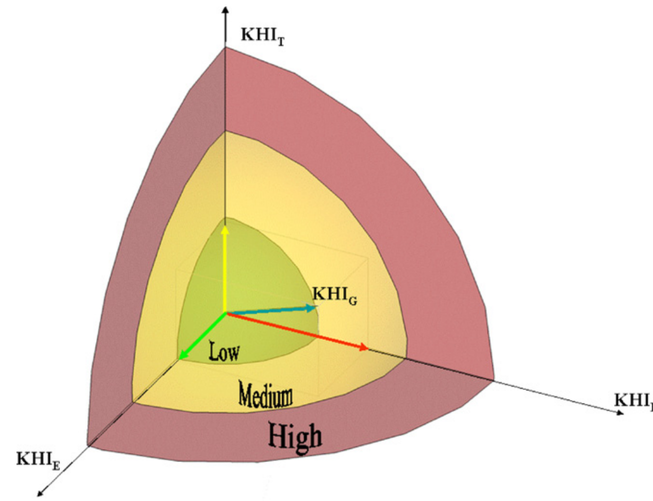


Fig. 1. KHI$_G$,which represents the overall risk level in the KHIs space.

three distinct KHIs: KHI$_F$, KHI$_T$, and KHI$_E$, for fires, toxic dispersion, and explosion, respectively.

Through simple mathematical manipulations [20], from the normalized values assigned to the alternatives, it is possible to compute the three KHIs values on a 0–1 scale. To determine the risk level of a given plant characterized by three values of KHI$_F$, KHI$_T$, and KHI$_E$, these values must be condensed into a global KHI (KHI$_G$), which should represent the overall risk level in the KHIs space. Because the origin of the 3D KHIs space represents the optimal condition (i.e., the lower the KHI value, the lower the related risk level), a point into the KHIs space, identified by the three values, KHI$_F$, KHI$_T$, and KHI$_E$, represents a risk level related to its distance from the origin. Therefore, KHI$_G$ can be evaluated through a norm providing the distance from the origin, which in a 3D space can be simply obtained as the square root of the sum of the three squared KHIs:

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

This range can be grouped into a low (<10^{-2}), medium (10^{-2}–10^{-1}) or high (>10^{-1}) sensitivity bracket in regards to the Na-Tech events of the analyzed process, as shown in Fig. 1.

Highly rated plants require further Na-Tech risk analysis, while lowly rated plants do not; however, the Na-Tech risk related to medium rated plants is neither negligible nor unacceptable. This is a sort of ALARP (as low as reasonably practicable) region [22], where the decision on how much further the Na-Tech risk assessment must be conducted, is determined by the analyst and must be decided on a case-by-case basis.

3. Hierarchies

3.1. Hierarchy for fires (KHI$_F$)

The KHI$_F$ should represent the impacted area related to fires (e.g. fireball, flash fire, or pool fire) arising from a Na-Tech event.

The elements that primarily influence the impacted area are the specific thermal power of the stored material and the specific flow of combustible vapors arising from the released materials. This leads to the hierarchy summarized in Fig. 2, which is composed of the fundamental objective (KHI$_F$), two levels related to the two main elements identified (in terms of combustion enthalpy and volatility), and the alternatives representing the plant/position characteristic. Each "alternative" is characterized by an overall normalized index, $\bar{M}_{hb}$ (where h indicates the hierarchy F, T or E, while

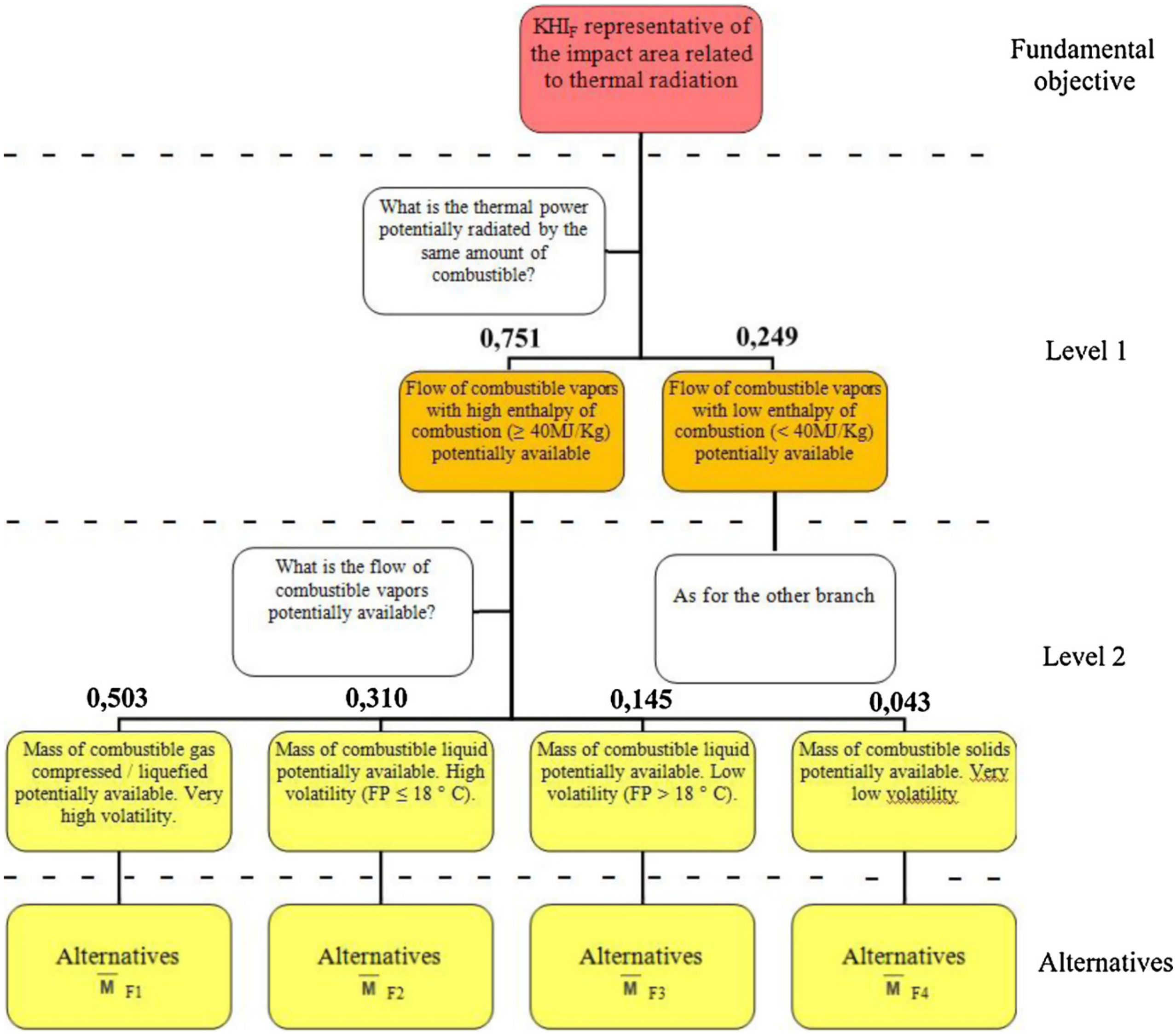


Fig. 2. Hierarchy used for earthquake-related Na-Tech qualitative risk analysis in case of fires. The weights assigned are shown along the different branches, while the related question to be answered is located above each level.

b indicates a branch of a hierarchy) of the amount of a given class of substances, which is expected to be released in case of a seismic event with a given intensity. Clearly, a branch may not be utilized (the branch has zero weight in calculating the index), depending on the characteristics of the materials present in the considered plant. Analogously, one or two of the three hierarchies may be not used (e.g., in the case of toxic substances that are neither flammable nor explosive). On the other hand, a volatile flammable material characterized by toxic vapors will be input of both the hierarchy for fires and the hierarchy for toxic dispersion.

Since the characterization of a given plant in a specific environment, which represents the different alternatives to be utilized in the hierarchy, is common to the three hierarchies (KHI_F, KHI_T, and KHI_E), it will be discussed in detail later. Here it suffices to mention that a given plant located in a specific environment is characterized by the ensemble of the basic alternatives.

Once the hierarchy is defined, it is necessary to compare the relevance of the hierarchy branches on the same level; such comparisons are expressed as qualitative judgments, which can be made quantitative through the semantic scale of Saaty. This procedure results in the definition of a matrix of the pair-wise comparison for each level from which it is possible to compute (through the normalized eigenvector of the matrix) the weight of each branch with respect to the others [20].

The relative importance among the different branches of the same hierarchy were defined on the basis of technical rules-of-thumb. In particular, “moderate importance”, corresponding to a value of 3 according to the semantic scale of Saaty, was assigned to materials with a higher combustion enthalpy because radiation from fire increases linearly with the combustion enthalpy. Much more weight was given to the more volatile substances because radiation is proportional to the burning velocity and, therefore, to the rate of flammable vapor production (for more details see Table 1).

3.2. Hierarchy for toxic dispersion (KHI_T)

KHI_T represents the impact area of a Na-Tech related release of toxic materials that can disperse into the atmosphere.

In this case, the principal elements are the toxicity (summarized in the IDLH value) and the volatility of the released material. This leads to the hierarchy summarized in Fig. 3, which is constituted by the Fundamental Objective (KHI_T), two levels related to

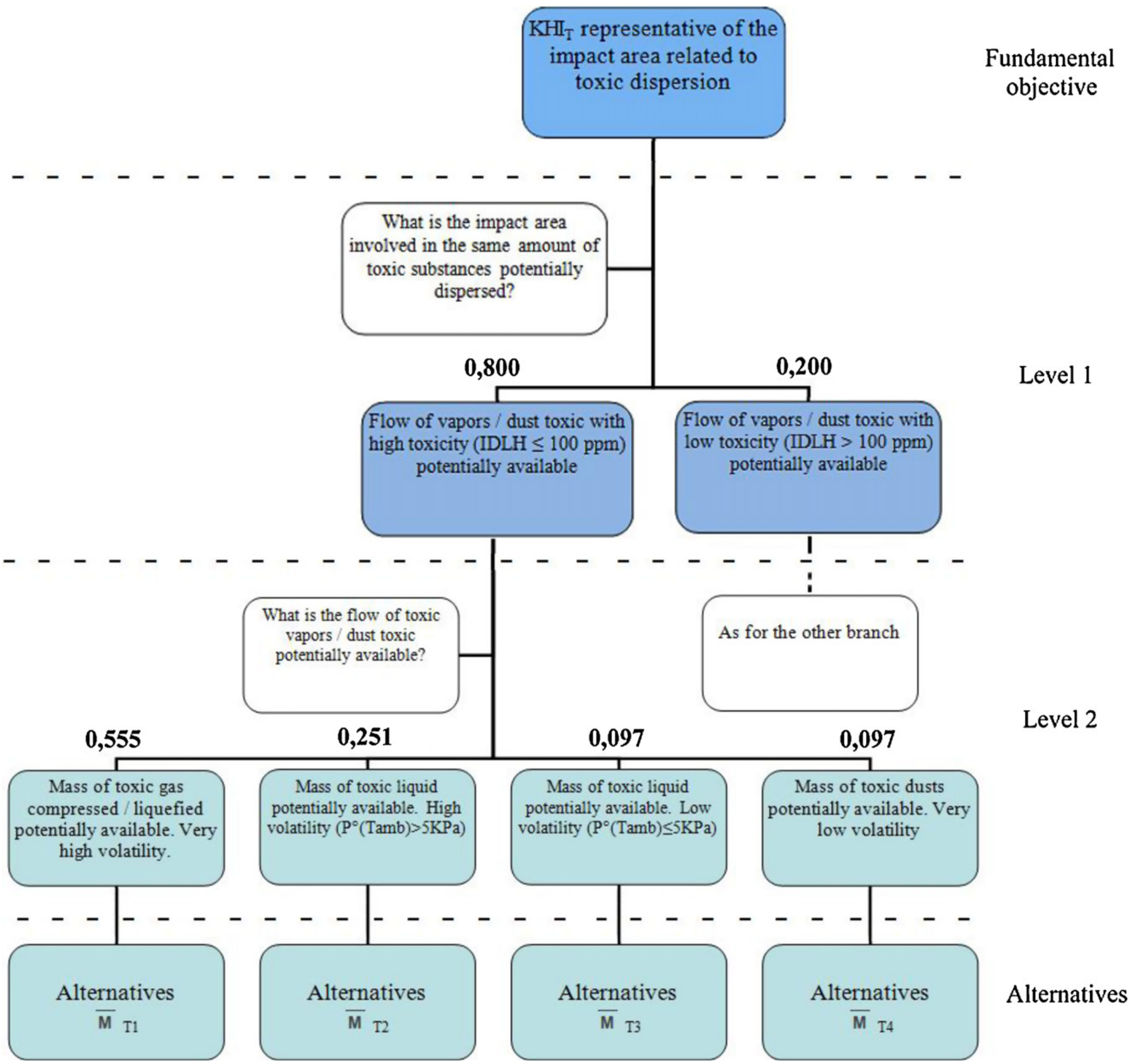


Fig. 3. Hierarchy used for the earthquake-related Na-Tech qualitative risk analysis in case of a toxic dispersion. The weights assigned are shown along the different branches, while the related question to be answered is located above each level.

the two main elements identified (toxicity and volatility), and the alternatives.

In addition, the relative importance of the various branches has been defined through pair-wise comparisons.

A value between "moderate importance" and "strong importance", corresponding to a value of 4 according to the semantic scale of Saaty, was assigned to substances with higher toxicity because a rather conservative limit was adopted to discriminate between more toxic and less toxic substances. Concerning volatility, much more importance was given to substances that emit larger amounts of vapor at ambient temperature (see Table 2). Different values were used in cases of flammable and toxic materials. This is primarily because the two phenomena (i.e., fire radiation and toxic vapors dispersion) are influenced differently by the relative volatility of the released materials.

3.3. *Hierarchy of explosions (KHI$_E$)*

KHI$_E$ represents the impact area of a Na-Tech event leading to an explosion; the principal elements correspond to the type of energy released (mechanical or chemical), the specific energy (in terms of pressure or combustion enthalpies), and the volatility (for vapor cloud explosion, VCE), as summarized in Fig. 4.

Pair-wise comparisons of the energy source account for different probabilities of a physical explosion (e.g., an explosion following the loss of containment of a pressurized vessel or a BLEVE) or an explosion of a vessel containing a flammable material (VCE).

The two events are characterized by different probabilities of occurrence: for the occurrence of a VCE, a large cloud of flammable vapors has to be generated, expand itself until it drops into the flammability limits and then ignite; for the occurrence of a physical explosion, the loss of containment suffices, therefore, a value of 7, which is "very strong importance" according to the semantic scale of Saaty, has been assigned.

Because the energy available for a VCE is proportional to the enthalpy of combustion, a value of 3, "moderate importance", according to the semantic scale of Saaty, was assigned to the materials with a higher enthalpy of combustion.

Moreover, more weight has been assigned to substances that produce larger quantities of flammable vapors at ambient

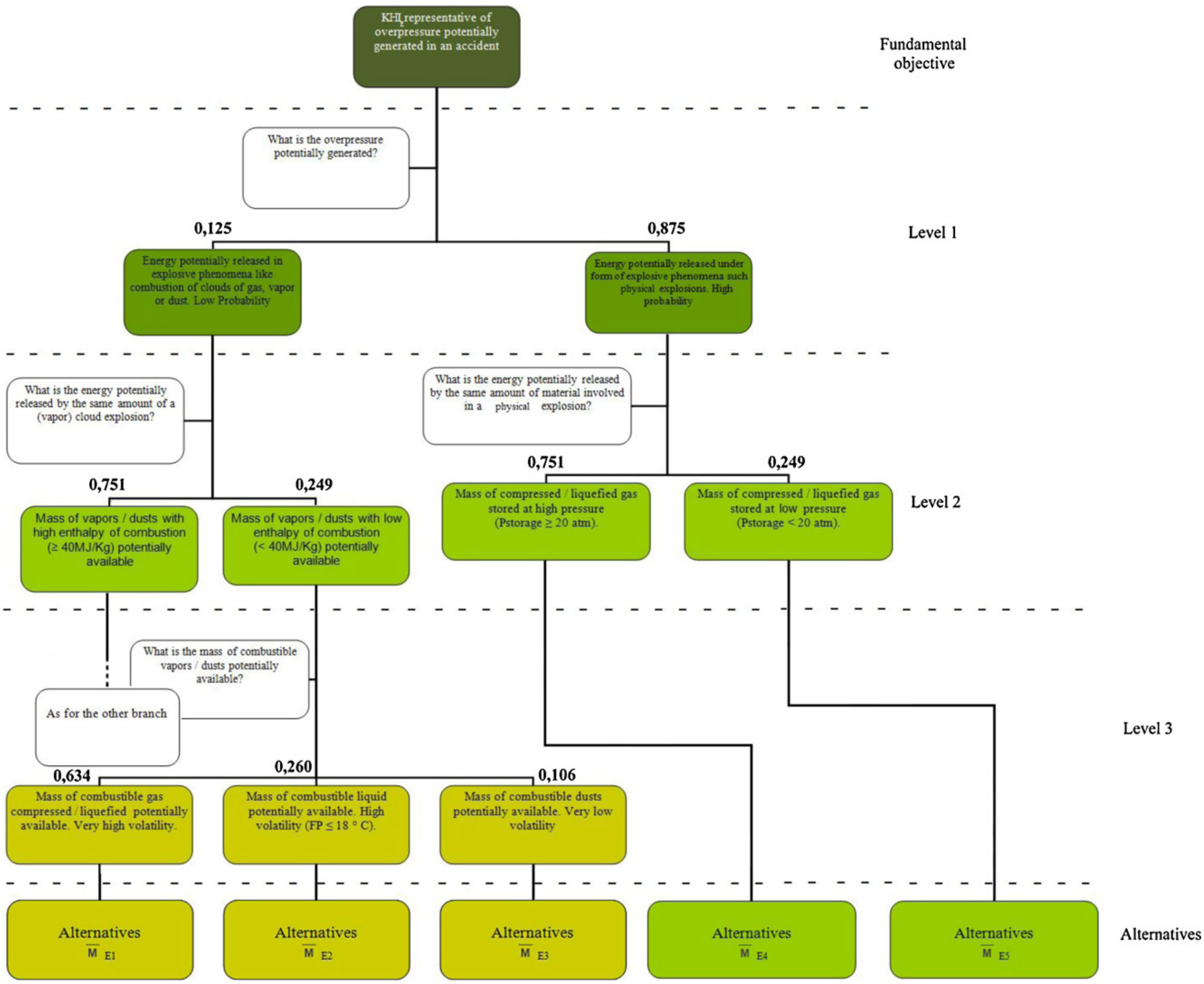


Fig. 4. Hierarchy used for earthquake-related Na-Tech qualitative risk analysis in case of an explosion. The weights assigned are shown along the different branches, while the related question to be answered is located above each level.

temperature; Table 2 shows examples summarized in terms of their relative volatility.

In physical explosions, the energy released is proportional to the storage pressure. Consequently, "moderate importance", corresponding to a value of 3 according to the semantic scale of Saaty, was selected for materials stored at higher pressures.

4. Evaluation of the alternatives: characteristics of the plant/earthquake

For each branch, a normalized index of the mass of similar materials (i.e., capable of generating similar scenarios in terms of effects), which can be released following a seismic event having a certain intensity, should be provided. The procedure for the calculation of the normalized indexes $\bar{M}_{hb}$ (h corresponds to one of the three hierarchies T, F, or E and b corresponds to one of the branches of the hierarchy) is summarized in the block diagram of Fig. 5, which also considers the possibility of a domino effect.

The first step of the procedure is to identify a reference peak ground acceleration (PGA) value at which the plant may be exposed due to an earthquake in the region where the plant is located. The exceeding probability of PGA occurrence is currently available for several regions worldwide [23], while seismic loads are usually determined from the maximum PGA expected over a given time interval, typically the one having an exceedance probability of 10% in 50 years. Therefore, a suitable reference PGA can be selected as follows:

$$\overline{\mathrm{PGA}} = \mathrm{PGA@10\%exceedance\ probability}$$

However, any other reference value can be selected at the convenience of the analyst, for instance, when intensity versus probability function is not known. Once the reference $\overline{\mathrm{PGA}}$ value is selected for each tank in the plant, the material contained has to be classified according to its hazardous properties. This can be done according to the European Chemicals Bureau (Council Directive 67/548/EEC), which has classified substances in various classes depending on their properties. Toxic substances, classified as T +, T, C, Xi, Xn, N, will feed the $\mathrm{KHI_T}$ hierarchy, flammable substances classified as F+ or F will feed the $\mathrm{KHI_F}$ and $\mathrm{KHI_E}$ hierarchy, while pressurized gaseous substances will fed the $\mathrm{KHI_E}$ hierarchy.

Therefore, the seismic fragility for each tank at the identified $\overline{\mathrm{PGA}}$ must be computed. This can be done through the vulnerability curves (tanks were considered completely filled for conservative reasons). These curves provide the probability of the a tank collapse (i.e., worst scenario) at a given $\overline{\mathrm{PGA}}$ value as a probit function y [15], whose K_1 and K_2 coefficients are summarized in Table 3:

$$y = K_1 + K_2 \ln(\overline{\mathrm{PGA}})$$

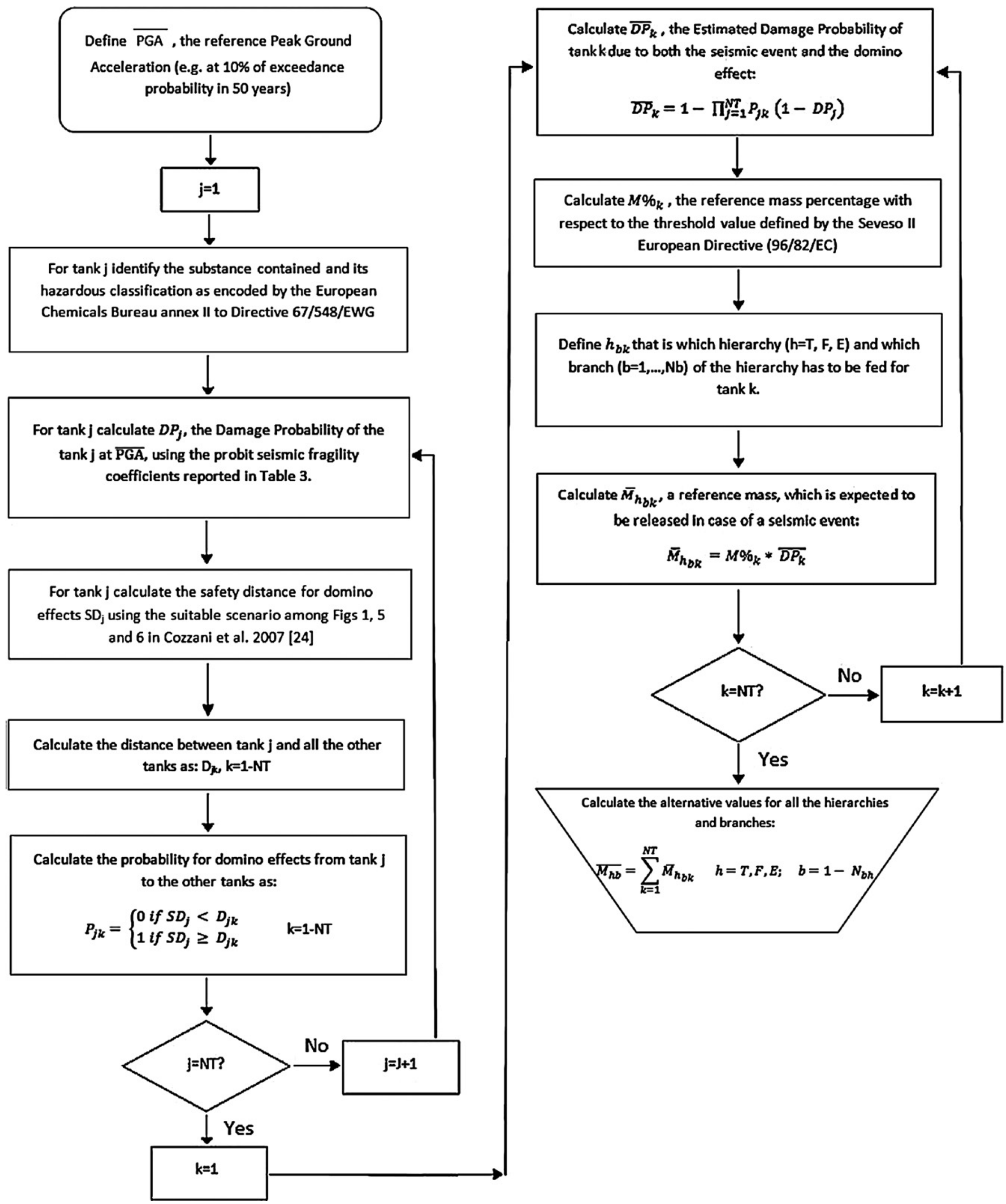


Fig. 5. Procedure for the evaluation of alternatives in the hierarchy; NT is the total number of tanks in the plant; N_{bh} is the number of branches in the hierarchy being considered (see Figs. 2–4).

where $\overline{\mathrm{PGA}}$ is expressed as a fraction of the gravity constant $g = 9.8\ \mathrm{m/s^2}$ and y is related to the probability of a tank collapse DP_j, by means of simple integration [22].

To account for a domino effect (i.e., the possibility of the collapse of another tank triggered by the collapse of the first tank due to an earthquake), a "safety distance" short-cut approach was used [24]. This assumes that the escalation probability is equal to zero if the distance between the damaged tank and the target tank is larger than a threshold value (otherwise it is equal to one).

The threshold distance value corresponding to an escalation depends on the scenario arising from the earthquake-damaged tank, which can be approximated from the results reported in

Table 2
Paired comparison matrices of the relative relevance of the various hierarchical branches for: (a) Fires; (b) Toxic dispersions (c) Explosions. See the semantic scale of Saaty (Table 1 for the meaning of the numeric values).

(a)

	Compressed/ liquefied gas	High volatility liquid	Low volatility liquid	Solid
Fires				
Compressed/liquefied gas	1	2	4	9
High volatility liquid	1/2	1	3	7
Low volatility liquid	1/4	1/3	1	5
Solid	1/9	1/7	1/5	1

(b)

	Compressed/ liquefied gas	High volatility liquid	Low volatility liquid	Dusts
Toxic dispersions				
Compressed/liquefied gas	1	3	5	5
High volatility liquid	1/3	1	3	3
Low volatility liquid	1/5	1/3	1	1
Dusts	1/5	1/3	1	1

(c)

	Compressed/ liquefied gas	High volatility liquid	Dusts
Explosions			
Compressed/liquefied gas	1	3	5
High volatility liquid	1/3	1	3
Dusts	1/5	1/3	1

Cozzani et al. [24]. When the earthquake-damaged tank creates a fireball, the safety distance is estimated as:

$$SD = \exp(0.345\ln(V) + 3.018)$$

where SD is the threshold distance, (m) for the escalation and V (m^3) is the vessel volume.

In the case of a pool-fire scenario arising from light hydrocarbons, such as gasoline, and when the target is an atmospheric tank, the following equation is relevant:

$$SD = \frac{m}{5000} + 50$$

where m is the inventory of the primary tank (kg). If the target is a pressurized vessel the previous relation becomes the following:

$$SD = \frac{m}{5000} + 15$$

These two relations are slightly modified when the primary tank contains heavy hydrocarbons (like fuel oil), leading to the following equations:

$$SD = \frac{m}{2000} + 50$$

$$SD = \frac{m}{2000} + 15$$

These equations refer to atmospheric tanks and pressurized vessels as targets, respectively.

Table 3
Seismic fragility in terms of probit coefficients [15].

Type of tank	K_1	K_2
Anchored atmospheric	4.66	1.54
Unanchored atmospheric	5.51	1.34
Horizontal pressurized	3.39	1.12

When the earthquake-damaged tank releases flammable vapors leading to a VCE, the following relationships can be used:

$$SD = \exp\ (0.333\ln(E) + 1.312) + 0.51E^{1/3}$$

$$SD = \exp\ (0.333\ln(E) + 1.535) + 0.51E^{1/3}$$

The former applies to atmospheric tanks as a target, while the latter refers to pressurized vessels. E is the energy of the released vapors (MJ). The last term in these equations arises from the assumption of a hemispherical cloud of air/flammable vapors with an average combustion energy of 3.6 MJ/m^3.

Comparing the distance between certain tanks (D_{jk}) and their relative safety distances, the probability of domino effects from each tank to the others (P_{jk}) can be computed by the following:

$$P_{jk} = \begin{cases} 0 & \text{if} \quad D_{jk} > SD_j \\ 1 & \text{if} \quad D_{jk} < SD_j \end{cases}$$

where D_{jk} is the distance between tanks, while SD_j is the related safety distance.

The overall damage probability, ($\overline{DP_k}$), considering the domino effect, can be estimated (for the k-th tank) as:

$$\overline{DP_k} = 1 - \prod_{j=1}^{NT}(1 - DP_j P_{jk})$$

where NT is the number of tanks in the plant.

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

$$\overline{M_{hbk}} = M_{\%k}\ \overline{DP_k}$$

The relative mass percentage contained in tank k is computed with respect to the threshold value defined by the Seveso II European Directive (Council Directive 96/82/EC). If the directive does not indicate a threshold for the material in the tank, it will not be considered in the analysis.

The subscript hbk indicates which hierarchy (h = T, F, E) and which branch ($b = 1, \ldots, N_{bh}$) of the hierarchy has to be utilized for tank k on the basis of the substance classification. More than one hbk can be defined for each tank depending on the substances stored in the plant.

Once a reference mass is computed for all the tanks present in the plant, the alternative values for all the hierarchies and branches ($\overline{M_{hb}}$) can be computed as follows:

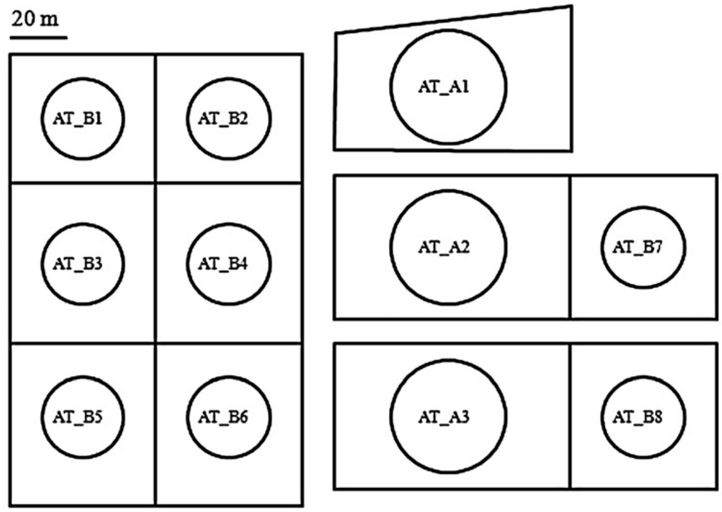
$$\overline{M_{hb}} = \sum_{k=1}^{NT} \overline{M}_{hbk} \quad h = T, F, E \quad b = 1, \ldots, N_{bh}$$

where N_{bh} is the number of branches in the h-th hierarchy.

5. Validation

The case studies reported below are derived from available layouts of existing oil refineries, for which results from a detailed QRA considering also Na-Tech events are available [15]. This allows a comparison between the results of the proposed simplified method and the results of a much more detailed QRA to be performed.

The layouts sketched in Figs. 6–8 show the position, number, and catch basins of the units considered in the analysis. The boundaries of the plant section considered are also evidences. According to



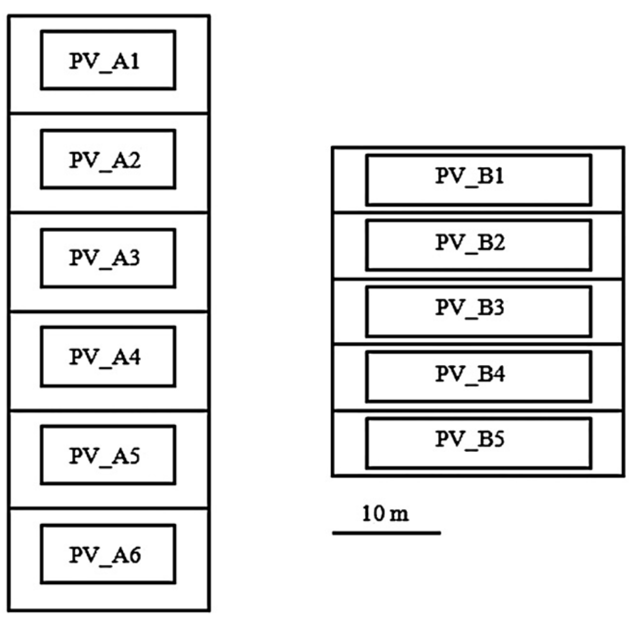
Unit	Type	Geometry	Diameter, m	Height, m	Substance
AT_A1-3	Atmospheric	Vertical cylinder	56	5.4	gasoline
AT_B1-6	Atmospheric	Vertical cylinder	38	7.2	gasoline
AT_B7-8	Atmospheric	Vertical cylinder	46	7.2	gasoline

Fig. 6. The layout and main design characteristics for a process plant in Milazzo [15].

design standards, each unit is identified by an identification code (e.g., AT A1, AT B1, etc.).

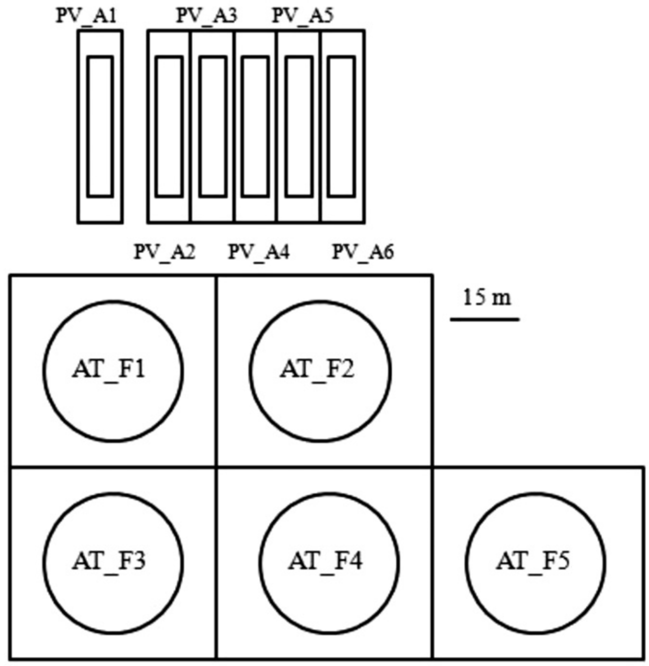
Because historical analytical methods reveal that in the case of industrial accidents triggered by natural events, storage tanks are the most likely to produce dramatic accidental scenarios, reactors, pumps, pipes, and other items were overlooked.

Na-Tech quantitative risk assessment is characterized by a high numerical complexity; it therefore needs to be implemented in specific codes that summarize the results in several risk indexes. The risk index used for the comparison with the KHI_G, obtained by the methodology presented in this paper, is the PLL (potential life loss), i.e., the average expected frequency of fatalities



Unit	Type	Geometry	Diameter, m	Height, m	Substance
PV_A1-6	Pressurized	Horizontal cylinder	6	13	LPG
PV_B1-5	Pressurized	Horizontal cylinder	3.5	20	LPG

Fig. 7. The Layout and main design characteristics for a process plant in Roma [15].



Unit	Type	Geometry	Diameter, m	Height, m	Substance
AT_F1-5	Atmospheric	Horizontal cylinder	35	10	gasoline
PV_A1-6	Pressurized	Horizontal cylinder	4	40	LPG

Fig. 8. The layout and main design characteristics for a process plant in Livorno [15].

due to accidental events in the target area. PLL is calculated as follows:

$$PLL = \int_0^\infty F\ dN$$

where F is the cumulative frequency of accidents and N is the expected number of fatalities [17,18,22].

As suggested by the purple book [25], it was considered only the worst case scenarios in the analysis of loss of containments (LOCs) and a conservative value of 100% for ignition probability was assumed.

5.1. Case study 1

In Fig. 6, the layout and the main design characteristics of case study 1 are reported, while data on the earthquake are shown in Table 4, together with PLLs resulting from QRA. Details on each unit, identified by the correspondent unit code, are reported in Table 5. For this case, characterized by atmospheric tanks, different types of equipment items (anchored and unanchored) were considered in the analysis. Consequently, the values of PLL reported ($PLL_{overall\ (seismic+internal)}$) refer to both anchored and unanchored storage tanks that were considered to be almost full, and in worst damage state, i.e., instantaneous release of the entire content. The PLL value for a catastrophic event without the seismic event ($PLL_{internal}$) was also reported. These PLL values were calculated from the F–N curve obtained using the vulnerability of anchored and unanchored storage tanks, respectively [15]. When seismic events were considered in the analysis, the PLL values increased from one to two orders of magnitude, depending on the type of atmospheric tanks considered (anchorage reduced the seismic vulnerability of the tanks). Details on the computations conducted following the simplified approach proposed are summarized in Table 5 together with details on the computations of the simplified approach, while the overall KHI_G value is reported in Table 6 with the corresponding ranking (i.e., low, medium, or high); the same table also reports a comparison between the QRA results (in terms of the ratio between PLL considering Na-Tech events and PLL disregarding them) and the results of the simplified method proposed in this work.

The rank obtained with the proposed short-cut method was in good agreement with the results obtained from the QRA: where the presence of the seismic event entailed an increment of two order of

Table 4
Data for the earthquakes studied and PLLs resulting from QRA [15].

Case study	PGA (g)	Occurrence (years^{-1})	$PLL_{overall\ (seismic+internal)}$ (fatalities/year) With seismic event	$PLL_{internal}$ (fatalities/year) no seismic event
1a: Milazzo anchored	0.302	1.0E-04	2.9E-03	1.4E-05
1b: Milazzo unanchored	0.302	1.0E-04	3.9E-04	1.4E-05
2: Roma	0.159	1.0E-04	3.8E-04	3.7E-04
3: Livorno	0.143	1.0E-03	8.5E-04	6.0E-04

Table 5
Quantities of substances stored, corresponding thresholds of the Seveso II Directive and information on the vulnerability of stocks and intensity of domino effect in the case studies of the facilities of Milazzo, Roma and Livorno [15].

Case study	Tank name	Tank type	Substance	Mass (10^3 kg)	Seveso II limit (10^3 kg)	Relative mass % $M_{\%k}$	Damage probability DP_j	Domino effect	Overall damage probability $\overline{DP}_k$
Milazzo An (1a)	AT-A1-A3AT-B1-B8	Anchored atmospheric	Gasoline	67,661	50,000	135	1.45E-02	Yes, atmospheric	7.16E-02
Milazzo Un (1b)	AT-A1-A3AT-B1-B8	Unanchored atmospheric	Gasoline	67,661	50,000	135	1.37E-01	Yes, atmospheric	8.07E-01
Roma (2)	PV-A1-A6PV-B1-B5	Pressurized	LPG	1304	200 200	652	1.22E-04	Yes, pressurized	1.18E-03
Livorno An (3)	AT-F1-F5	Anchored atmospheric	Gasoline	28,849	50,000	58	4.26E-04	Yes, atmospheric and pressurized	2.41E-03
	PV-A1-A6	Pressurized	LPG	1242	200	621	7.58E-05	Yes, pressurized	4.56E-04

Table 6
Comparison between the results of the proposed procedure and that of a QRA [15].

Case study	$PLL_{Int+Seismic}/PLL_{Int}$	KHI_G	Rank
1a: Milazzo anchored	2.8E01	2.3E-02	Medium
1b: Milazzo unanchored	2.1E02	2.3E-01	High
2: Roma	1.0E00	3.3E-03	Low
3: Livorno An	2.0E00	1.5E-03	Low

magnitude of the PLL value, the proposed simplified method provided a high ranking; while when the PLL increment was different by one order of magnitude, it displayed a medium score.

5.2. Case study 2

In Fig. 7, the layout and the main design characteristics of case study 2 are reported, while data concerning the seismic event for the site considered and the relative PLL values obtained by the QRA are summarized in Table 4. Details on each unit, identified by the correspondent unit code, are reported in Table 5 together with details on the computations of the simplified approach and Table 6 reports the overall KHI_G value and the corresponding ranking. The same tables also reports a comparison between the results obtained from the QRA [15] and the simplified method.

Coherently, the proposed method provided a "low" KHI rank being the PLL values computed considering and disregarding the Na-Tech event of the same order of magnitude. This reduction in the Na-Tech risk was due both to the lower PGA value and the lower vulnerability of pressurized tanks, with respect to case study 1, which prevailed on the larger hazard of LPG in respect to gasoline.

5.3. Case study 3

In Fig. 8, the layout and the main design characteristics of case study 3 are reported, while data concerning the seismic event for the site considered and the relative PLL values obtained by the QRA are shown in Table 4. Table 5 reports same details on the simplified approach computations as for case study 1 and 2, Table 6 shows the final results in terms of both KHI_G and overall ranking. In spite of the more hazardous properties of LPG with respect to gasoline, the pressurized tanks were less vulnerable to earthquakes than the atmospheric tanks, which led to a lower KHI_G value with respect to case study 1. A comparison between the results obtained from the QRA report and those from the simplified screening method presented in this paper exhibited good agreement: the resulting ranking from the simplified approach was "low", while QRA predicts PLL values with and without earthquake of the same scales of magnitude.

6. Conclusions

Because earthquakes may be powerful and prominent mechanisms of direct and indirect Hazmat releases, earthquake related Na-Tech events might increase the impact and the overall damage in surrounding areas of industrial sites.

The aim of this study was to provide a referential short-cut methodology for the assessment of industrial risks induced by earthquakes through suitable KHIs computed using the Analytical Hierarchy Process [20].

The methodology developed required very few resources and little information on both the plant and the expected earthquake. Therefore, it would be suitable at any stage of a plant's life (i.e., from the early design stage to an already existing plant).

Finally, the developed methodology was validated by a comparison with independent results obtained by a QRA report [15] in terms of the ratio between PLL values in presence and absence of the seismic event showing a good agreement. When QRA in the presence of a seismic event entailed an increment of two orders of magnitude on the PLL value, the proposed simplified method provided a "high" value for KHI_G; when QRA foresaw an increment of approximately one order of magnitude, the proposed approach provided a "medium" level score; when almost no increment of the PLL value was predicted by the QRA, the proposed approach provided a "low" KHI_G ranking.

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References

[1] S. Young, L. Balluz, J. Malilay, Natural and technologic hazardous material releases during and after natural disasters: a review, Science of the Total Environment 322 (2004) 3–20.
[2] A. Galderisi, A. Ceudech, M. Pistucci, A method for Na-Tech risk assessment as supporting tool for land use planning mitigation strategies, Natural Hazards 46 (2008) 221–241.
[3] L.J. Steinberg, H. Sengul, A.M. Cruz, Natech risk and management: an assessment of the state of the art, Natural Hazards 46 (2008) 143–152.
[4] P.S. Showalter, M.F. Myers, Natural disasters in the United-States as release agents of oil, chemicals, or radiological materials between 1980 and 1989 – analysis and recommendations, Risk Analysis 14 (1994) 169–182.
[5] A.M. Cruz, L.J. Steinberg, L. Vetere-Arellano, Emerging issues for natech disaster risk management in Europe, Journal of Risk Research 9 (2006) 483–501.
[6] J.I. Chang, C.-C. Lin, A study of storage tank accidents, Journal of Loss Prevention in the Process Industries 19 (2006) 51–59.
[7] K. Rasmussen, Natural events and accidents with hazardous materials, Journal of Hazardous Materials 40 (1995) 43–54.
[8] J.S. Picou, Katrina as a Natech disaster, in: Toxic Contamination and Long-Term Risks for Residents of New Orleans, University of South Alabama, 2009.
[9] A.M. Cruz, E. Krausmann, Hazardous-materials releases from offshore oil and gas facilities and emergency response following Hurricanes Katrina and Rita, Journal of Loss Prevention in the Process Industries 22 (2009) 59–65.
[10] A.M. Cruz, N. Okada, Methodology for preliminary assessment of Natech risk in urban areas, Natural Hazards 46 (2008) 199–220.
[11] V. Cozzani, M. Campedel, E. Renni, E. Krausmann, Industrial accidents triggered by flood events: analysis of past accidents, Journal of Hazardous Materials 175 (2010) 501–509.
[12] R. Fendler, Floods and safety of establishments and installations containing hazardous substances, Natural Hazards 46 (2008) 257–263.
[13] E. Krausmann, F. Mushtaq, A qualitative Natech damage scale for the impact of floods on selected industrial facilities, Natural Hazards 46 (2008) 179–197.
[14] V. Cozzani, R. Bandini, C. Basta, M.D. Christou, Application of land-use planning criteria for the control of major accident hazards: a case-study, Journal of Hazardous Materials 136 (2006) 170–180.
[15] M. Campedel, V. Cozzani, A. Garcia-Agreda, E. Salzano, Extending the quantitative assessment of industrial risks to earthquake effects, Risk Analysis 28 (2008) 1231–1246.
[16] G. Fabbrocino, I. Iervolino, F. Orlando, E. Salzano, Quantitative risk analysis of oil storage facilities in seismic areas, Journal of Hazardous Materials 123 (2005) 61–69.
[17] G. Antonioni, S. Bonvicini, G. Spadoni, V. Cozzani, Development of a framework for the risk assessment of Na-Tech accidental events, Reliability Engineering and System Safety 94 (2009) 1442–1450.
[18] G. Antonioni, G. Spadoni, V. Cozzani, A methodology for the quantitative risk assessment of major accidents triggered by seismic events, Journal of Hazardous Materials 147 (2007) 48–59.
[19] R. Bell, T. Glade, Multi-hazard analysis in natural risk assessments, in: C.A. Brebbia (Ed.), Risk Analysis Iv, Wit Press, Southampton, 2004, pp. 197–206.
[20] T. Saaty, Fundamentals of decision making and priority theory with the analytic hierarchy process, Analytic Hierarchy Process Series (2000).
[21] R. Rota, S. Caragliano, D. Manca, S. Brambilla, A short cut methodology for flood-technological risk assessment, Chemical Engineering Transactions (2008) 53–60.
[22] F.P. Lees, in: Mannan (Ed.), Lees' Loss Prevention in the Process Industries, vol.1–3, 3rd Ed., Sam © 2005 Elsevier, 1996.
[23] J.J. Bommer, Deterministic vs. probabilistic seismic hazard assessment: An exaggerated and obstructive dichotomy, Journal of Earthquake Engineering 6 (2002) 43–73.
[24] V. Cozzani, A. Tugnoli, E. Salzano, Prevention of domino effect: from active and passive strategies to inherently safer design, Journal of Hazardous Materials 139 (2007) 209–219.
[25] P.A.M. Uijt de Haag, B.J.M. Ale, Guidelines for Quantitative Risk Assessment, Purple Book, 1st ed., Committee for the Prevention of Disasters, CPR 18E, The Hague, 1999.