Definition of a short-cut methodology for assessing the vulnerability of a territory in natural–technological risk estimation

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1. Introduction

Natural disasters may be powerful and prominent mechanisms of direct or indirect release of hazardous material [1]. In fact, when industrial sites are located in naturally hazard-prone areas, loss of containments and technological accidents may be induced by natural events, leading to the so-called NaTech (Natural–Technological) accidents [2].

In recent years, NaTech events have received a significant attention and several reviews on NaTech events have been published [3–11]. Recent examples of NaTech events are reported in the literature [12–15], but only a few works discuss approaches and methodologies necessary to face the problems they cause [2,14,16–18].

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) to situations wherein an industrial accident is triggered by a natural event [10,19–22]. A limitation of the QRA is that it requires a large amount of resources in terms both of time and expertise; thus, short-cut methodologies for the assessment of industrial risks induced by natural events, easy to handle and capable of taking into account the most important phenomena that occur in a NaTech event, have been developed for screening purposes, i.e., for deciding when it is worthwhile to conduct a QRA [23,24]. However, such procedures do not account for the land use of the territory, giving information in some way similar to the individual risk through the computation of suitable Key Hazard Indicators, KHIs.

In this work, a simple methodology that can assess the vulnerability of a territory considering the characteristics of the population (density and distribution) and the presence of vulnerable centers (hospitals, schools, fire stations and so on) was developed with the aim of complementing the aforementioned KHIs, therefore leading to information in some way similar to the societal risk.

In fact, the combined use of the Global Key Hazard Indicator (KHI_G), obtainable through the methodologies previously developed [23,24], with the key vulnerability indicator (KVI) resulting from the application of the methodology herein presented, allows the measurement of the NaTech Risk level imposed by the presence of the plant in a territory with a given vulnerability. The developed procedure was validated by comparing its predictions with some QRA results involving earthquake-related NaTech events. The main use of the methodology developed in this work is to discriminate between high-risk situations, for which it is necessary to undertake a QRA and to provide risk mitigation measures, and low-risk situations, therefore avoiding wasting of resources using unnecessary expensive methods of Risk Analysis.

Moreover, the KVI can also be used (as a part of a decision support system) as a stand-alone screening procedure for the evaluation of the opportunity to establish a plant in a given territory.

2. Methodology

The seismicity (frequency and force which an earthquake occurs with) is a physical characteristic of the considered territory: the

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seismic hazard is defined as the probability that in a given area and in a certain interval of time an earthquake exceeding a defined threshold of intensity, magnitude, or peak ground acceleration (PGA) can occur. The predisposition of a structure to be damaged by an earthquake is defined vulnerability. The more a structure is vulnerable the more severe the expected consequences will be. The greater or lesser presence of assets at risk and, therefore, the consequent possibility of being subjected to a damage (in human lives, economic and cultural terms, etc.), is defined exposure (of life, of economic assets, of cultural heritage, etc.).

The seismic risk is therefore determined by the combination of these three factors: hazard, vulnerability and exposure; it is a measure of the damages, which, depending on the type of seismic activity, resistance of the structures, and human activities (nature, quality and quantity of exposed goods), can be expected in a given interval of time.

The presence in the considered territory of industrial plants, which hold and use hazardous substances for their activities, exposes the population and the surrounding environment to a given industrial risk. In contrast to the one related to natural events, the industrial risk is associated to human activities.

In particular, the industrial risk is associated with the release of hazardous substances which by their nature, quantity, or processing procedures can cause damage to the population and the environ-ment, trough: fires, explosion and dispersion of toxic substances.

However it has to be distinguished between effects and consequences of an undesired event. For instance, an effect of fires is heat radiation, while a consequence is people burning.

A short-cut procedure should be easy to apply, require a small amount of resources and information and summarize, through a suitable key vulnerability index (KVI), the level of vulnerability associated to a given territory around an industrial plant.

Estimating the value of such KVI requires a simultaneous comparisons among different parameters, ranging from the characteristics of population to the presence of vulnerable centers [25]. Thus, a multi-criteria decision method is necessary to account for the different and often incommensurable effects of various parameters. Among the various approaches available, the analytical hierarchy process, AHP [26] has been used: it can support decision making by establishing alternatives within a framework of multi-weighted criteria. This method allows for choosing among various alternatives through binary comparison, that is, considering only two elements at a time. The idea of using the AHP in the context of NaTech risk analysis has been recently proposed [27], and two practical short-cut procedures for earthquake and flood related NaTech events have been developed [23,24]. In this case, the use of the AHP requires the identification of all the main elements that can determine the vulnerability of the territory; such elements, while covering all the relevant aspects, should be few and easy to evaluate.

All the details of using the AHP for developing a short-cut methodology in the field of risk analysis are not reported in the present paper since they are extensively discussed elsewhere [23]; here it suffices to mention that binary comparisons between elements must be established, and they must be arranged in a suitable hierarchy structured with the goal on top (in this case the KVI), with different branches. At the bottom of the hierarchy there are the alternatives that characterize the given territory. Through simple mathematical manipulations [26], from the normalized values assigned to the alternatives, it is possible to compute the KVI value on a 0–1 scale.

Hierarchy branches (structured at different levels) represent a breakdown into sub-goals. Considering that AHP 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 answer to the same question.

The hierarchy proposed to evaluate the KVI is summarized in Fig. 1 where we can see that the branches are distributed over two levels, referring to the following two questions:

(1) Which kind of accident could happen into a plant?
(2) What are the elements that mostly influence the vulnerability of the area affected by NaTech event?

Once the hierarchy is defined, it is necessary to compare the relevance of the hierarchy branches at the same level; such comparisons are expressed as qualitative judgments, which can be made quantitative through the semantic scale of Saaty [26]. This procedure results in the definition of the matrix of 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 [26].

The relative importance among the different branches of the same hierarchy was defined on the basis of technical rules-of-thumb. For what concern the first question, we distinguished between two main phenomena, the “fire/explosion” and the “toxic dispersion” event: the assigned relative importance into the matrix of pairs’ confrontations is 1, so the importance of the two criteria is equal. This lead to the same weight, equal to 0.5.

For what concern the second question the presence of vulnerable centers is statistically significant only when they involve a high number of people with respect to the population density; the threshold was set at 200 inhabitants per square kilometer. This value is consistent with the information contained in the Italian EPP guidelines [28] and it is obviously a simplification (consistent with the expeditious nature of the method) meaning that for highly populated areas the presence of vulnerable centers does not influence significantly the number of affected people and does not increase significantly the difficulty in managing the emergency. On the basis of this assumption the most important criterion is therefore the number of people present on the considered area which allows to assign the relative importance into the matrix of pairs confrontations equal to 5, “significantly more important”; this lead to weights respectively for the number of people and vulnerable centers equal to 0.833 and 0.167.

After having assigned a weight to each identified criteria, it is necessary to determine the input values of the hierarchy, which are the alternatives.

Due to the expeditious nature of the presented methodology, the choice of using the medium density of population at municipal level for computing the number of people is a reasonable choice if more detailed data are not available.

The elements to be considered as vulnerable can be identified according to the following parameters:

- difficulty of evacuation of weak and needy subjects (sick, children, elderly);
- difficulty to evacuate subjects in buildings higher than 5 floors or large aggregations of people in public places;
- higher vulnerability of outdoor activities respect to the indoor ones;
- lower vulnerability of the activities characterized by a short time of permanence of people, which results in less exposure to risk, compared to activities that require longer time of permanence.

A complete list of main vulnerable sites to be considered can be found in the work of Bonvicini et al. [29]; here just a few are listed for the sake of examples:

- hospitals, barracks
- schools of all levels

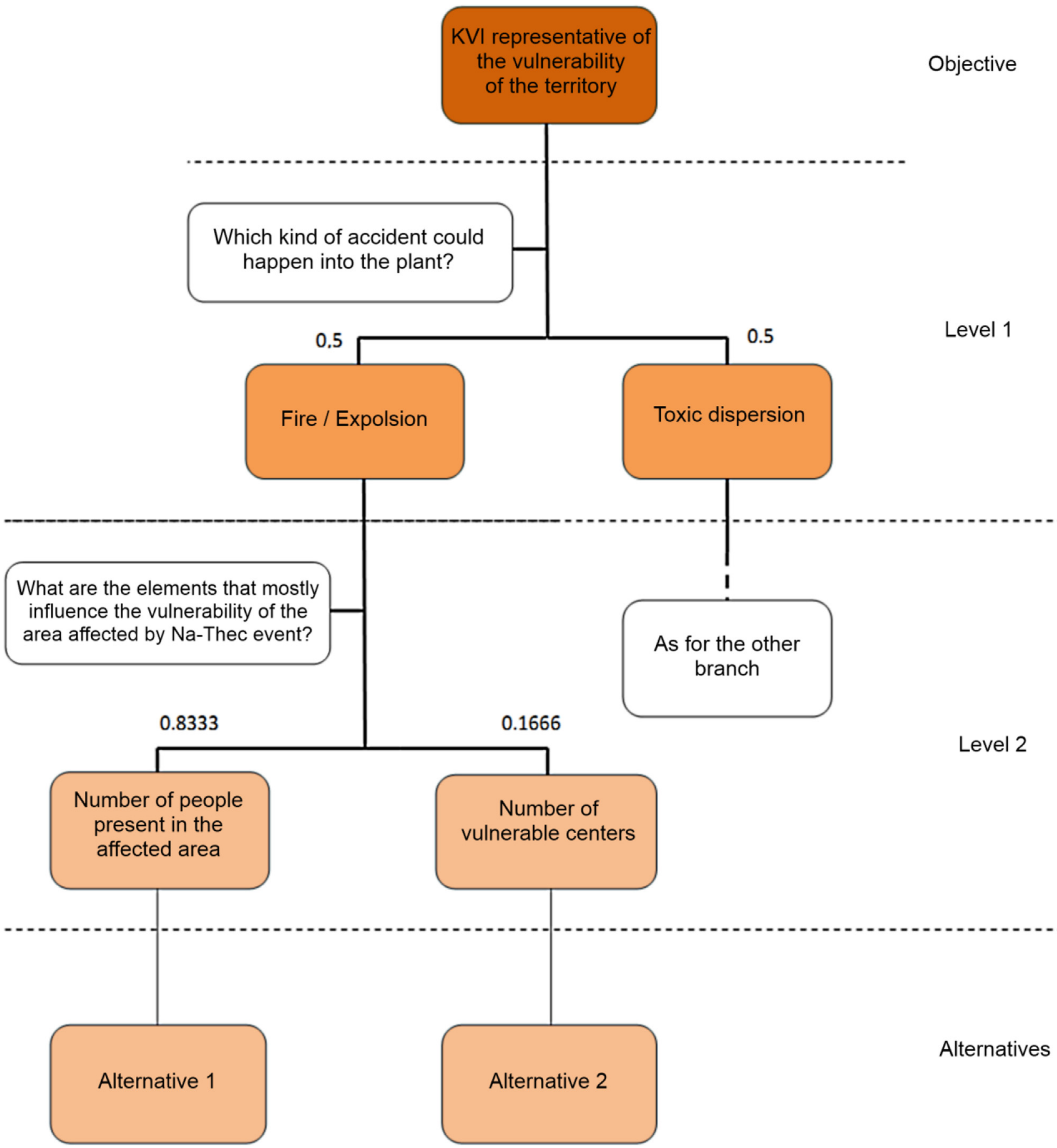

Fig. 1. Hierarchy for the calculation of the KVI.

- museums or tourist sites
- shopping centers
- auditorium
- municipalities, courts, post offices
- stadiums, arenas, racetracks, sports centers
- main places of worship
- railway stations, public transport stations, airports
- parks, fairs

As stated before, we distinguish between two main phenomena: the "fire/explosion" and the "toxic dispersion" event; this choice implies the splitting of the hierarchy into two branches at the first level, the level immediately subsequent the main objective. The main difference between these two different events is the portion of involved territory. We chose to consider as critical for events such as fire/explosion an area of 1 km radius from the border of the plant, while an area of 7 km radius for events such as dispersion of toxic substances. These values, although conservatives, are similar to that found in typical case-histories involving fire/explosion or dispersion of toxic substances, and they are also consistent with the information contained in the Italian EEP guidelines [28]. Each of the two branches has symmetrical development, but the variation of the impact areas related to the phenomenology of the two different kinds of accident leads to a substantial difference in the amount of people potentially affected by the events.

Once defined the impact area of the NaTech event (1 km or 7 km radius for fire/explosion or toxic dispersion branch), the next

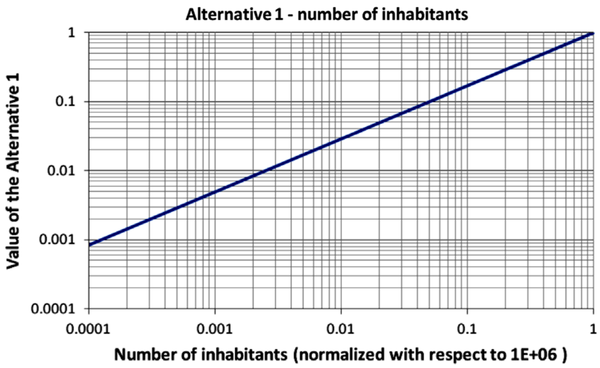

Fig. 2. Number of inhabitants into the considered area and corresponding values for Alternative 1.

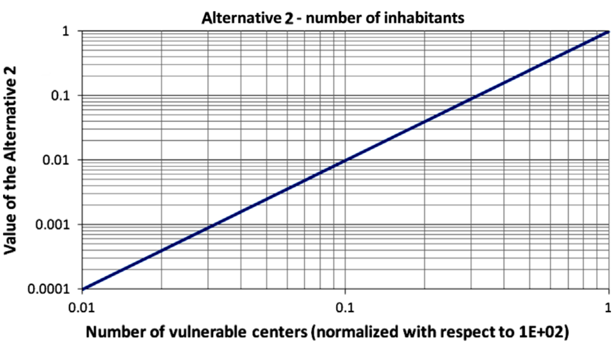

Fig. 3. Number of vulnerable centers into the considered area and corresponding values for Alternative 2.

step is the quantification of the number of individuals present in the area, determined by the population density (and distribution, if known) and the number of vulnerable centers present in the area. The value of the alternative related to presence of population into the considered area can be computed from the diagram in Fig. 2, defined in order to deal with both small areas with a low number of people and large areas with a high number of people. This diagram is also consistent with the zoning method described into the Italian EEP guidelines [28].

For what concern the number of vulnerable centers, if it is small the emergency is manageable; consequently, a quadratic rule for the alternative was used, as shown in Fig. 3.

Thus, summarizing, the KVI computation requires the evaluation of both the number of people and the number of vulnerable centers present inside 1 km and/or 7 km radius, depending by the kind of hazardous substances stored into the plant. Then, using the diagrams of Figs. 2 and 3, the values of the alternatives for the fire/explosion branch (1 km radius data) and the toxic dispersion branch (7 km radius data) are defined and fed to the hierarchy.

Once KVI value is computed, an overall risk indicator can be estimated.

In particular, risk can be considered as a combination of hazard and vulnerability; the first one is given by the KHI resulting from previously validated methodologies [23,24], while the second one is given by the KVI resulting by the methodology herein presented.

As a simple tool for the synthesis of the two indices is the risk matrix summarized in Table 1: crossing the values of KHI (rows) with values of KVI (columns) we can obtain the relative index of risk (KRI). The matrix substantially let us to simply weight the value of the KHI (Hazard), independent then from the human settlements in the territory, by considering the presence of population and Vulnerable Centers outside the plant thanks to the KVI (Vulnerability).

The proposed methodology was validated by comparing its prediction with that of a much more detailed QRA carried out for a

Table 1
Risk matrix for the synthesis of KHI and KVI into KRI.

KRI	$KVI > 10^{-1}$ (HIGH)	$10^{-1} > KVI > 10^{-2}$ (MEDIUM)	$KVI < 10^{-2}$ (LOW)
$KHI > 10^{-1}$ (HIGH)	HIGH	HIGH	MEDIUM
$10^{-1} > KHI > 10^{-2}$ (MEDIUM)	HIGH	MEDIUM	LOW
$KHI < 10^{-2}$ (LOW)	MEDIUM	LOW	LOW

few case-studies. A suitable risk index computed from the QRA (considering also NaTech events) is the potential life loss (PLL) defined as:

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

where F is the cumulative frequency of accidents and N is the expected number of fatalities [23]. Unfortunately, there is no accepted standard worldwide for societal risk. In the following the UK criteria are used, which define as a lower threshold value for unacceptable societal risk the boundary line with an anchor point of 10^{-2} and slope of -1, while the boundary line with the same slope and an anchor point of 10^{-4} represents the upper threshold of the acceptable risk region [30,31]. Computing the PLL values from these boundaries lead to the following qualitative classes for PLL (fatalities/year) values: $PLL < 10^{-3}$=LOW, $10^{-3} < PLL < 10^{-1}$=MEDIUM, $PLL > 10^{-1}$=HIGH.

In the following, four different case-study involving earthquake-related NaTech accidents are presented.

3. Validation of the methodology

3.1. Case study 1: Milazzo

The first case study refers to a realistic plant in Milazzo previously presented in the literature [22,23]. Information about PGA, type of tanks, PLL, KHI_G and the resulting classification of the risk are shown in Table 2.

For the evaluation of the KVI the accidental scenarios must be defined; from the QRA [22] it can be seen that in this case only scenarios like fires are possible since the substance contained into the tanks is gasoline. Therefore, only the branch on the left side of the hierarchy has to be fed; the corresponding area will have a radius of 1 km.

From the QRA [22] we can deduce also the information related to the population density (1000 inhabitants/km^2) and the number of vulnerable centers in the considered area (0).

Since there are no vulnerable centers, the Alternative 2 will assume a value equal to 0, while the Alternative 1 requires the calculation of the effective number of people present on the considered area (3141 inhabitants). This corresponds from the diagram in Fig. 2 to a value for the Alternative 1 equal to about 1.7E−2. The value of the KVI (equal both for anchored and unanchored storage tanks) is lower than 10^{-2}, therefore resulting in a LOW classification.

Crossing the two classes of KHI and the KVI in the risk matrix we can obtain the KRI for the two different cases, anchored and unanchored storage thanks, as shown in Table 2. We can see that the risk classification obtained with the proposed procedure fairly agrees with that from QRA.

3.2. Case study 2: Rome

The second case study refers to a realistic plant in Rome previously presented in the literature [22,23]. Information about

Table 2
PGA, type of tanks, PLL classes from the QRA values [22], KHI classes [23], and the resulting classification of the risk (KRI) for case studies 1–3.

		PGA	KHI	KVI	KRI	PLL class
Case study 1 (Milazzo)	Anchored tanks	0.302	Medium	Low	Low	Low
	Unanchored tanks		High	Low	Medium	Medium
Case study 2 (Roma)	Pressurized tanks	0.159	Low	Low	Low	Low
Case study 3 (Livorno)	Pressurized and atmospheric tanks	0.143	Low	Low	Low	Low
Case study 4 (Lombardia)	Pressurized and atmospheric tanks	0.1	Medium	High	High	High

PGA, type of tanks, PLL, KHI_G and the resulting classification of the risk are shown in Table 2.

For the evaluation of the KVI the accidental scenarios must be defined; from the QRA [22] it can be seen that in this case only scenarios like fires/explosions are possible since the substance contained into the tanks is LPG. Therefore, only the branch on the left side of the hierarchy has to be fed; the corresponding area will have a radius of 1 km.

From the QRA [22] we can deduce also the information related to the population density (1000 inhabitants/km^2) and the number of vulnerable centers in the considered area (0).

Since there are no vulnerable centers, the Alternative 2 will assume a value equal to 0, while the Alternative 1 requires the calculation of the effective number of people present on the considered area (3141 inhabitants). This corresponds from the diagram in Fig. 2 to a value for the Alternative 1 equal to about 1.7E−2. The value of the KVI is lower than 10^{-2}, therefore, resulting in a LOW classification.

Crossing the KHI and the KVI in the risk matrix we can obtain the KRI value, shown in Table 2. We can see that the risk classification obtained with the proposed procedure fairly agrees with that from QRA.

3.3. *Case study 3: Livorno*

The third case study refers to a realistic plant in Livorno previously presented in the literature [22,23]. Information about PGA, type of tanks, PLL, KHI_G and the resulting classification of the risk are shown in Table 2.

For the evaluation of the KVI the accidental scenarios must be defined; from the QRA [22] it can be seen that in this case only scenarios like fires/explosions are possible since the substances contained into the tanks are gasoline and LPG. Therefore, only the branch on the left side of the hierarchy has to be fed; the corresponding area will have a radius of 1 km.

From the QRA [22] we can deduce also the information related to the population density (1000 inhabitants/km^2) and the number of vulnerable centers in the considered area (0).

Since there are no vulnerable centers, the Alternative 2 will assume a value equal to 0, while the Alternative 1 requires the calculation of the effective number of people present on the considered area (3141 inhabitants). This corresponds from the diagram in Fig. 2 to a value for the Alternative 1 equal to about 1.7E−2. The value of the KVI is lower than 10^{-2}, therefore resulting in a LOW classification.

Crossing the KHI and the KVI in the risk matrix we can obtain the KRI value, shown in Table 2. We can see that the risk classification obtained with the proposed procedure fairly agrees with that from QRA.

3.4. *Case study 4: Lombardia*

The Lombardia Region (located in the north of Italy) is characterized by the presence of important chemical and petrochemical industries, high populated areas and seismic hazard (the area is classified as Zone 3 according to the Italian seismic zones, corresponding to a PGA between 0.05 and 0.15 g with exceedence probability of 10% in 50 years). This area has therefore the characteristics required for validating the proposed procedure. The data used for the case study represent a realistic situation, in particular, the territorial data and the natural hazard data comes from the real data of Lombardia region, while the industrial plant data are realistic data. The plant has been located within an existing industrial area with chemical inventories taken from a typical process plant.

Table 3
Damage frequencies used in the QRA performed in case study 4.

	Internal causes	Seismic causes [PGA 0,1 g]
Damage frequency for pressurized tanks	5.4E−05	1.0E−05
Damage frequency for anchored atmospheric storage tanks	7.15E−05	1.0E−04
PLL	6.05E−02	4.233

The plant considered for the case study has an extension of 50,000 m^2 and involves the following items:

- 10 pressurized tanks containing ethylene;
- 5 atmospheric tanks containing diesel;
- 2 pressurized tanks containing methanol;
- 1 pressurized tank containing ammonia;
- 1 pressurized tank containing chlorine.

The population density in the area considered is equal to 1935 inhabitants/km^2 and some vulnerable centers are present. More specifically, 10 vulnerable centers are located within 1 km, while 19 vulnerable centers have been found within 7 km from the plant location.

Accidental scenarios have been defined on the basis of credible accidents, also following the suggestions reported in the “Purple Book” [32].

Damage frequency for the considered tanks and for the damage state of interest, i.e. the catastrophic collapse, is also required. They have been token from the literature [33] for internal causes events, while in case of seismic event with a given PGA have been calculated using to probit functions [22], as summarized in Table 3.

The ARIPAR-GIS Tool, considering also NaTech events, has been used for QRA. This Tool is based on a series of procedures aimed at assessing, in quantitative terms, the risk associated with the processing, storage and transportation of hazardous substances in industrial areas.

The societal risk, in terms of the *F–N* curve, both for internal and seismic causes was evaluated and the resulting PLL, reported in Table 3, corresponds to a high risk classification.

Following the procedure explained in detail elsewhere [23], the KHI value for the considered plant can be computed as equal to 0.017, corresponding to a medium hazard classification.

For the evaluation of the KVI the accidental scenarios must be defined; it can be seen that in this case both scenarios like fires/explosion and toxic dispersion are possible. Therefore, both

Table 4
Data used for the calculation of the KVI.

	Territory
Population density	1935 [inhabitants/km^2]
	Fire/explosion phenomena
Considered area	3.142 [km^2]
Population involved	6079 [inhabitants]
Vulnerable centers involved	10
	Dispersion phenomena
Considered area	153.938 [km^2]
Population involved	297870 [inhabitants]
Vulnerable centers involved	19

branches have to be fed; the corresponding area will have a radius of 7 km.

In Table 4 information about population and number of vulnerable centers in the considered area are reported leading to a KVI equal to 0.224, corresponding to a high vulnerability classification.

Crossing the KHI and the KVI in the risk matrix we can obtain the KRI for the case shown in Table 2. Results obtained by the confrontation between the KRI obtained thanks to the application of the shortcut methodologies and the PLL obtained thanks to the QRA herein performed using ARIPAR-GIS tool show a good agreement further confirming the validity of the methodologies developed.

4. Conclusions

The value of KHI defined elsewhere [23] returns a level of inherent hazard of the plant related to NaTech events, thus independent from the anthropic level of the considered territory: this gives information in some way similar to the individual risk. In this work, a procedure able to introduce information that allow discriminating the outcome of the final index (KRI) as a function of the human presence in the areas potentially affected by the NaTech events was developed and validated by comparison with independent results from QRA.

The convergence of the KRI values obtained with this methodology with the PLL values resulting from QRA in all the analyzed case studies supports the validity of the methodology developed. Further advancements of the proposed methodology could involve, for the sake of example, the presence of other industrial equipment (pipelines, reactors, etc.) as well as accounting also for the coping capacity in the KHI calculation.

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