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The Description of Population Vulnerability in Quantitative Risk Analysis

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The description of the distribution of population in the potential impact areas of accident scenarios is of utmost importance for the assessment of the final consequences of potential accidents. Vulnerability centers (i.e., sites where the simultaneous presence of a relevant number of persons in a narrow area is anticipated) may play an important role in this framework. In this study a method for the correct and detailed description of offsite target population in potential impact areas of major accidents is developed. The method is aimed at supporting quantitative risk analysis studies, emergency planning, and land-use planning. An approach is suggested to define the population categories that should be taken into account and to provide criteria for indoor and outdoor population distribution in vulnerability centers. Case studies are also provided to understand the outcomes and the potentialities of the methodology.

KEY WORDS: Emergency planning; land-use planning; major accident hazard; offsite population; quantitative risk analysis; vulnerability

1. INTRODUCTION

The improvement of safety in the process industry has been a major concern in all industrialized countries over the last three decades. In Europe the Seveso Directives[1–3] provide a common framework for the control of risk posed by major accident hazards. Quantitative risk analysis (QRA) is nowadays a standard tool, adopted both by industry and control authorities, to assess the safety of industrial installations where dangerous substances are present.

Although QRA is a consolidated and widely used technique, a few issues still need to be addressed in detail. One of these is the description of the distribution of the population that can be affected by the adverse consequences of accidents.[4–9] To evaluate the number of persons that may be involved in major accidents having offsite consequences, data on offsite population distribution around the industrial installation of interest are necessary. In this framework, it is also necessary to gather information on the population present at specific sites, the so-called vulnerability centers (e.g., schools, hospitals, and shopping malls). Collecting these data is a necessary step in the calculation of the societal risk caused by industrial sites.[10–15] Data on population are necessary also for land-use planning (LUP) activities with respect to major accident hazards[16–19] and for external emergency planning around hazardous industrial sites.[20,21] More generally, information on population is necessary for all types of emergency planning, such as those concerning natural disasters (as earthquakes and floods) or other more specific events that may involve industrial installations, as NaTech accidents[22,23] and malicious intentional interferences.[23]

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The availability of geographical information system (GIS) software allows a detailed representation of population distribution.[15,24–29] Population is usually represented introducing a limited number of population categories.[10,11,28–32] Statistical data for each population category are then obtained, defining day/night, indoor/outdoor, seasonal, and other average probabilities of presence. In the absence of specific information, typical densities of resident population may be defined as a function of the type of area (e.g., urban, suburban, and rural zones.[10,11,13,30,33,34]

In more recent studies,[35,36] an effort was made to consider vulnerability centers besides resident population. A vulnerability center may be defined as a site where a relevant number of persons may be present in a narrow area. Information on vulnerability centers is crucial to define the priorities in emergency management after an incident and to identify the best protective actions to be undertaken. Even if the definition of vulnerability centers was not specifically addressed in most of the previous studies, several important cornerstones concerning this issue are present in authoritative references.[11–13,17,30,33,37–39]

The retrieval of information and the correct representation of the distribution of population in accident potential impact areas are critical and time-consuming issues.[15] A key topic in the management of major accident hazards is to select the correct level of detail to effectively represent the population.[4,37] In this study a method is developed for the description of offsite target population in potential impact areas of major accidents. The method specifically addresses the definition of vulnerability centers, also introducing different approaches for the assessment of presence probabilities of different population categories. The results of a validation by case studies are also discussed.

2. METHODOLOGY PROPOSED FOR THE DESCRIPTION OF POPULATION

2.1. Aim of the Methodology

The aim of this study is to propose a methodology for the description of offsite population, mainly aimed at a detailed calculation of societal risk indexes. A specific methodological approach is presented to address the description of offsite population in areas surrounding industrial sites. Criteria were developed to identify the vulnerability centers that need to be considered both with respect to risk assessment and for emergency planning. Further criteria were provided to identify the significant population categories and to assess the yearly average probability of presence and the indoor presence probability.

2.2. Resident Population and Onsite Workers

A population may be divided in a limited number of categories having similar habits. In particular, population categories may be defined considering individuals having similar probabilities of presence on a site of interest and a similar vulnerability to the adverse effects of accidents.[10,12,37] The standard approach used for the description of a population in QRA studies is based on the definition of at least two main population categories: residents and onsite workers. Table I shows some assumptions concerning the probability of presence adopted for the description of resident population in authoritative literature sources.[10,31,32,34,37] Information on the number of workers present within the site, their duties and their usual workplace, as well as on available protection devices are used to obtain data for onsite workers.[40]

2.3. Vulnerability Centers and Nonresident Population

Besides resident population and onsite workers, other categories of population may be present in an impact area of an accident.[15] For instance, if the explosion that occurred at the AZote et Fertilisants (AZF) ammonium nitrate plant in Toulouse (France) is considered,[41] the accident consequences affected some car drivers on a nearby motorway and the workers of other companies in the vicinity of the accident site. The fire and explosion of a propylene tank car at San Carlos de la Rapita (Spain) in 1978 caused 215 fatalities and 67 injuries, all among the tourists present in a camping site.[37]

However, important difficulties arise in the description of offsite nonresident population. Due to the very different probabilities of presence of different population categories, a specific analysis is needed in the framework of QRA and of emergency management. Even if some official documents propose a list of vulnerability centers that should be considered in this framework,[17,28,29,42,43] scarce attention is devoted to the problem and no complete and well accepted list of vulnerability centers to be considered in QRA, emergency planning, or LUP is available in the literature. Expert judgment was

Table I. Assumptions for the Probability of Presence and for Indoor Presence Probability of Resident Population Adopted in Some Major QRA Studies[10,31,32,34,37]

Ref.	Time Period (j)	$PP\%_{Res,j}$	$P\text{indoor}_{Res,j}$	$P\text{outdoor}_{Res,j}$
10	Daytime (8.00–18.30)	80–85	0.93	0.07
	Nighttime (18.30–8.00)	–	0.99	0.01
31	Daytime	42	–	–
	Nighttime	100	–	–
32	Working time (26%)	46	0.99 (toxic clouds)	0.01 (toxic clouds)
	Nonworking time (73%)	100	0.90 (explosions)	0.10 (explosions)
34	Daytime (8.00–18.30)	70	0.93	0.07
	Nighttime (18.30–8.00)	100	0.99	0.01
37	Daytime (8.00–18.30)	100	0.50	0.50
	Nighttime (18.30–8.00)	–	0.75	0.25

only used to justify the exclusion from these lists of some categories of vulnerability centers (e.g., the list proposed by Italian regulations for emergency planning[43] does not consider hotels and transport infrastructures, such as railway stations and airports).

A first issue of this study was the systematic identification and the analysis of relevant categories of vulnerability centers. The analysis was based on the results of a previous research project carried out for the Italian National Civil Protection Department[44,45] to update the categories of vulnerability centers considered for emergency planning in the case of a major accident. The initial list proposed by the Italian Civil Protection Department was widened, including all the categories of vulnerability centers considered in official studies promoted by competent authorities in some of the more important Italian industrial areas.[25,36,46–51] The list obtained was checked for completeness by a door-to-door survey performed in the industrial areas of Ravenna and Livorno. Table II reports the list of the 52 different types of vulnerability centers and of the 74 categories of population[44,52] defined in the study. The correspondence of vulnerability centers with population categories is not one-to-one. In fact, more population categories may be present in a single vulnerability center and different vulnerability centers may share the same population category.

2.4. Definition of the Probability of Presence

For each population category included in Table II the probability of presence in the vulnerability centers was estimated on the basis of specific information and/or statistical data. Because this probability may vary from daytime to nighttime and also from season to season, four time periods were defined:

(1) hot season, daytime;
(2) hot season, nighttime;
(3) cold season, daytime; and
(4) cold season, nighttime.

In the present approach, the hot season was supposed to last from April to September and the cold season from October to March. Nighttime refers to the time from 18.00 to 6.00. Quite obviously, different day/night and season periods may be decided without affecting the general approach proposed. However, seldom does the adoption of a number of time periods higher than four seem to have any advantage, also considering the statistical origin of the data. In any case, the sum of the time extension of the periods has to be equal to one year.

For each category of population the average probability of presence (%) over the year, $PP\%_{\mathrm{AV},i}$, may be calculated as follows:

$$PP\%_{\mathrm{AV},i} = \sum_{j=1}^{N_{\mathrm{tp}}} PP\%_{i,j} F_j, \qquad (1)$$

where F_j is the time fraction of period j over one year, $PP\%_{i,j}$ is the presence probability of category i during period j, and N_{tp} the number of time periods in which the year has been divided.

To estimate the probability of presence data for each category of population and all time periods, two different approaches may be defined: the "Lagrangean" approach and the "Eulerian" approach. In the Lagrangean approach, the presence probability of a specific population category is evaluated from the stand of a person belonging to the category that estimates the time spent in the vulnerability

Table II. Vulnerability Centers and Corresponding Population Categories[44,52]

Id Code	Vulnerability Centers	Id Code	Population Categories	$PP\%_{AV,i}$ Lagrangean Approach	$PP\%_{AV,i}$ Eulerian Approach
C01	*Hospitals*	P01	Patients	0.6	100
		P02	Daytime workers (health service)	19.0	39.3
		P03	Shift workers (health service)	19.0	100
C02	*Old age homes*	P01	Patients	0.6	100
		P02	Daytime workers (health service)	19.0	39.3
		P03	Shift workers (health service)	19.0	100
C03	*Nursing homes*	P01	Patients	0.6	100
		P02	Daytime workers (health service)	19.0	39.3
		P03	Shift workers (health service)	19.0	100
C04	*Daytime centers for people with disabilities*	P01	Patients	0.6	100
		P02	Daytime workers (health service)	19.0	39.3
		P03	Shift workers (health service)	19.0	100
C05	*Social rehabilitation centers*	P01	Patients	0.6	100
		P02	Daytime workers (health service)	19.0	39.3
		P03	Shift workers (health service)	19.0	100
C06	*Nursery schools (0–2 years)*	P04	Scholars (1–2 years)	22.2	22.2
		P05	Workers (nursery school 1–2 years)	19.7	22.2
C07	*Nursery schools (3–5 years)*	P06	Scholars (3–5 years)	22.2	22.2
		P07	Workers (nursery schools 3–5 years)	19.7	22.2
C08	*Primary schools*	P08	Scholars (primary school)	17.4	17.4
		P09	Workers/teachers (primary school)	11.3	17.4
C09	*Secondary schools*	P10	Scholars (secondary school)	13.1	13.1
		P11	Workers/teachers (secondary school)	9.6	13.1
C10	Fixed outdoor markets	P12	Customers (outdoor markets)	1.0	16.8
		P13	Workers	16.8	16.8
C11	Lidos	P14	Guests	1.1	13.6
C12	*Centers for immigrants*	P15	Residents	56.5	56.5
C13	Health spa	P14	Guests	1.1	13.6
C14	Health resorts	P14	Guests	1.1	13.6
C15	Prefabs, mobile homes	P15	Residents	56.5	56.5
C16	Commercial centers	P16	Customers	1.9	46.5
		P17	Sales clerks	21.1	23.2
C17	Supermarkets	P16	Customers	1.9	46.5
		P17	Sales clerks	21.1	23.2
C18	Fixed trade fairs	P16	Customers	1.9	46.5
		P17	Sales clerks	21.1	23.2
C19	Indoor markets	P16	Customers	1.9	46.5
		P17	Sales clerks	21.1	23.2
C20	High schools	P18	Students (high school)	14.4	13.7
		P19	Workers (high school)	10.6	13.7
C21	Universities	P20	Students (university)	8.6	23.2
		P21	Workers (university)	21.1	23.2
C22	Libraries	P22	Library visitors/users	1.9	24.8
		P23	Cultural service workers	21.1	24.8
C23	Museums and art galleries	P24	Visitors (museums)	0.05	24.8
		P23	Cultural service workers	21.1	24.8
C24	Music/art/language schools	P22	Students (music/art schools)	1.9	24.8
		P23	Cultural service workers	21.1	24.8
C25	*Boarding schools*	P15	Residents	56.5	56.5
C26	*Prisons*	P25	Convicts	100	100
		P26	Prison workers	19.0	100
C27	Barracks	P27	Soldiers	88.5	100
C28	Convents	P28	Religious community members	88.5	100

(Continued)

Table II. *(Continued)*

Id Code	Vulnerability Centers	Id Code	Population Categories	$PP\%_{AV,i}$ Lagrangean Approach	$PP\%_{AV,i}$ Eulerian Approach
C29	Hotels (all year open)	P29	Guests (hotel)	1.0	51.0
		P30	Workers (hotel)	22.5	58.9
C30	Seasonal hotels	P31	Guests (seasonal hotel)	2.1	27.1
		P32	Workers (seasonal hotel)	13.4	31.3
C31	Parliaments	P33	Politicians	25.0	50.0
		P34	Office workers	21.1	27.0
C32	Justice courts	P35	Public office visitors	0.01	27.0
		P34	Justice courts workers	21.1	27.0
C33	Public administration offices	P35	Public office visitors	0.01	27.0
		P34	Office workers	21.1	27.0
C34	Ministries	P33	Politicians	25.0	50.0
		P34	Office workers	21.1	27.0
C35	Medical practices	P36	Patients	0.05	27.0
		P37	Workers	19.0	27.0
C36	Sport centers	P38	Sportsmen/members	2.2	42.9
		P39	Workers (sport centers)	19.8	42.9
C37	Post offices	P35	Customers (post office)	0.01	27.0
		P34	Workers (post office)	21.1	27.0
C38	Indoor cinemas	P40	Audience (cinemas)	0.9	25.2
		P41	Workers (cinemas)	12.1	25.2
C39	Indoor theatres	P42	Audience (indoor theatres)	3.1	5.2
		P43	Workers (indoor theatres)	10.5	5.2
C40	Open-air cinemas	P44	Audience (open-air cinemas)	0.3	2.7
		P45	Workers (open-air cinemas)	1.8	2.7
C41	Open-air theatres	P46	Audience (open-air theatres)	0.5	1.8
		P47	Workers (open-air theatres)	1.8	1.8
C42	Weekly outdoor markets	P48	Customers (weekly outdoor markets)	0.6	7.1
		P49	Workers (weekly outdoor markets)	7.1	7.1
C43	Sports stadia	P50	Spectators (stadium)	0.9	1.0
		P51	Employees (stadium)	1.0	1.0
C44	Indoor sports arenas	P52	Spectators (arenas)	0.9	2.0
		P53	Workers (arenas)	2.0	2.0
C45	Churches	P54	Weekday church visitors	1.0	3.6
		P55	Holiday church visitors	0.5	3.0
C46	Congress centers	P56	Congress participants	0.01	50.0
C47	Railway and metro stations	P57	Railway passengers	1.4	75.0
		P58	Metro passengers	0.4	75.0
		P59	Indoor railway and metro workers	20.5	46.5
		P60	Train drivers and onboard personnel	10.0	75.0
C48	Airports	P61	Passengers	0.1	100
		P62	Indoor airport workers	20.6	100
		P63	Onboard personnel	20.6	100
C49	Marinas	P64	Passengers (marinas)	0.05	34.6
		P65	Workers (marinas)	8.1	34.6
C50	Bus stations	P66	Bus passengers	0.8	58.4
		P67	Indoor bus station workers	20.5	46.5
		P68	Bus drivers	3.2	58.4
C51	Cemeteries	P69	Cemetery visitors	0.01	50.0
C52	Factories, artisan enterprises, farms, and animal husbandries	P70	Workers (factories)	21.1	21.1
		P71	Industry daytime workers	21.1	88.5
		P72	Industry shift workers	28.4	28.4
		P73	Artisans	25.0	25.0
		P74	Farm laborers	35.4	37.5

center of interest. When choosing the Eulerian approach, the presence probability values are estimated as an average for the vulnerability center, taking into account that different individuals belonging to the same population category may be present at different times in the same site. Thus, the Eulerian probability of presence expresses the value of the probability that any person belonging to the population category of interest is present in the center.

For instance, consider the daytime workers of a hospital (category "P02-Daytime workers (health service)" in Table II). This category of workers works for 36 hours a week (all during daytime). Considering an average of four weeks of holidays and 22 working weeks during the hot season and two weeks of holiday and 24 of working weeks during the cold season, the presence probabilities may be easily calculated by the Lagrangean approach. Presence probability values of 36.3% and 39.6% can be estimated for "hot season, daytime" and "cold season, daytime" periods, whereas 0% presence probability values are obtained in time periods "hot season, nighttime" and "cold season, nighttime." An average presence probability value of 19% is obtained for $PP\%_{AV,i}$.

The same average presence probability value is obtained considering shift workers in a hospital (category "P03-Shift workers (health service)" in Table II), although on the basis of a probability distribution among day and night periods.

If the Eulerian approach is considered, a 100% probability of presence should be considered for shift workers, although there will be different shifts over the day. For daytime workers the estimate is slightly more complex and requires keeping into consideration the service hours per day. If opening hours from 7.00 to 18.00 for six days a week are considered, the presence probability is equal to 78.6% for "hot season, daytime" and "cold season, daytime" periods, and of 0% for "hot season, nighttime" and "cold season, nighttime" periods. The average presence probability is thus equal to 39.3%.

As obvious, the product of the Lagrangean presence probability by the number of persons belonging to the category considered has to be equal to the product of the Eulerian presence probability by the number of persons simultaneously present on the site evaluated by the latter approach. Therefore, the two approaches are equivalent and not in contradiction.

The choice of the approach to be adopted should be on the basis of the data available. In fact, the data needed for the calculation of the presence probability are widely different. Table III reports the information necessary for the calculation of the presence probabilities for selected categories of population both by the Lagrangean and the Eulerian approach. If the shift personnel of a hospital is considered, using the Lagrangean approach the number of shift workers listed on the payroll of the hospital has to be known. In the Eulerian approach, it is necessary to know the average number of shift workers present at the same time in the hospital.

Estimates of both the Lagrangean and the Eulerian presence probability values for all population categories identified are listed in Table II. In Table III the presence probability values during the four time periods considered and the average presence probability value are reported. The table clearly shows that in the case of population categories for which there is scarce or no interchange of individuals (e.g., scholars and residents) the two approaches lead to similar presence probability values, whereas this is no longer true for other categories (e.g., shift workers). The table also evidences that the presence probability value calculated for residents on the basis of statistical data available for the Italian population[53] varies between 44.2% and 69.2% depending on the time period, with an average value of 56.5%. These data point out that it is very conservative to assume that resident population is always present in houses ($PP\%_{AV,Res} = 100\%$), as done in some QRA studies.[11,13,36,38]

The population in a vulnerability center may be present either outdoors or indoors, depending on the site. Thus, the conditional probability of outdoor presence ($P\text{outdoor}_{i,j}$) and of indoor presence ($P\text{indoor}_{i,j}$) were evaluated for each population category i in each time period j. Table IV shows the values of $P\text{outdoor}_{i,j}$ and $P\text{indoor}_{i,j}$ calculated for some population categories. It should be recalled that being inside a building may improve the protection from the adverse consequences of some types of accident scenarios (e.g., toxic cloud dispersions, fires), whereas for others (e.g., earthquakes, explosions) it may be a negative factor.

The presence probability values reported in Tables II–IV were obtained from different sources. In some cases, it was possible to refer to statistical data of the Italian census[53] (e.g., for category "P15-Residents"). For all categories referring to workers (e.g., "P05-Workers (nursery school one to two years)," "P17-Sales clerks," "P70-Workers (factories)," "P71- Industry daytime workers," "P72-Industry shift workers," etc.), the typical working

Table III. Population Categories: Presence Probability Data and Information Needed for Their Estimation[44,52]

Population Category (i)		Time Period (j)	"Lagrangean" Approach $PP\%_{i,j}$	$PP\%_{AV,i}$	Information to Retrieve	"Eulerian" Approach $PP\%_{i,j}$	$PP\%_{AV,i}$	Information to Retrieve
P01	Patients	1	0.6	0.6	Number of yearly admissions	100	100	Average number of patients present at the same time
		2	0.6			100		
		3	0.6			100		
		4	0.6			100		
P02	Daytime workers	1	36.3	19.0	Number of workers registered on the payroll	78.6	39.3	Average number of workers present at the same time
		2	0			0		
		3	39.6			78.6		
		4	0			0		
P08	Scholars (primary school)	1	25.6	17.4	Number of enrolled scholars	25.6	17.4	Number of enrolled scholars
		2	0			0		
		3	44.0			44.0		
		4	0			0		
P09	Workers (primary school)	1	16.7	11.3	Number of people working in the school	25.6	17.4	Average number of workers present at the same time
		2	0			0		
		3	28.6			44.0		
		4	0			0		
P15	Residents	1	44.2	56.5	Number of people living in the house	44.2	56.5	Number of people living in the house
		2	66.4			66.4		
		3	46.2			46.2		
		4	69.2			69.2		
P71	Industry shift workers	1	20.2	21.1	Number of workers registered on the payroll	84.6	88.5	Average number of industry shift workers present at the same time
		2	20.2			84.6		
		3	22.0			92.3		
		4	22.0			92.3		

time derived from the national contracts of the various sectors of industrial or commercial activities was considered. For scholars and students of all ages school opening times were collected and averaged. For categories related to visitors of centers open to the public (e.g., "P16-Customers", "P35-Public office visitors", "P44-Audience (open-air cinemas)", etc.) the opening times of the different types of centers were examined. Finally, for a limited number of categories for which such data were not available, phone interviews with the managers of the vulnerability center were carried out, and the results were refined by expert judgment.

It is important to remark that the probability values reported in Tables II–IV were assessed in the Italian context. Thus, these values represent best estimates to be used in the absence of specific local data. Caution should be adopted when applying such values to other countries where climate or habits may be different.

2.5. Equivalence Criteria Among Population Categories

To evaluate the contribution of different categories of population to societal risk and identify the more important population categories that should be considered in a QRA study, it is necessary that an equivalence criterion among the different population categories is established. After the approach adopted in previous studies,[17] resident population (category "P15-Residents" in Table II) was used as a reference and a simple equivalence coefficient $SEC_{\mathrm{Res},i}$ was defined for each population category.

If $N_{i,x}$ is the number of persons belonging to the ith population category present in a given vulnerability center x, the "simple" number of equivalent residents may be calculated as:

$$SNR_{i,x} = SEC_{\mathrm{Res},i} N_{i,x}, \qquad (2)$$

Table IV. Population Categories: Outdoor and Indoor Presence Probability Data[44,52]

Population Category (i)		Time Period (j)	$Pindoor_{i,j}$	$Poutdoor_{i,j}$
P02	Shift workers (health service)	1	1.00	0.00
		2	1.00	0.00
		3	1.00	0.00
		4	1.00	0.00
P08	Scholars (primary school)	1	0.60	0.40
		2	0.00	0.00
		3	0.90	0.10
		4	0.00	0.00
P15	Residents	1	0.70	0.30
		2	0.90	0.10
		3	0.90	0.10
		4	1.00	0.00
P50	Spectators (stadium)	1	0.00	1.00
		2	0.00	0.00
		3	0.00	1.00
		4	0.00	0.00

and the "simple" equivalence coefficient may be defined as:

$$SEC_{\mathrm{Res},i} = \frac{PP\%_{\mathrm{AV},i}}{PP\%_{\mathrm{AV,Res}}}, \qquad (3)$$

where $PP\%_{\mathrm{AV,Res}}$ is the average probability of presence calculated for resident population and $PP\%_{\mathrm{AV},i}$ is the mean probability of presence of the ith population category. In this study the presence probabilities obtained by the Lagrangean approach were used to calculate $SEC_{\mathrm{Res},i}$, but the same results can be obtained if Eulerian probabilities are adopted. Table V shows the simple equivalence coefficients and the number of residents equivalent to 100 persons belonging to category i, SNR_{100-i}, calculated for several categories of nonresident population. The numerical values of the equivalence criteria are based on the average presence probabilities of Table II, although the methodology for their calculation has a general validity and may thus be applied also using different input data.

It is worth to notice that usually the resident equivalence coefficient is lower than 1 because in general nonresident population is present for less time than residents. However, this is not the case for some specific population categories (e.g., "P01-Hospital patients"), which are supposed to be always present at the site.

The simple equivalence coefficient provides a first criterion to rank nonresident population categories and to address priorities in the analysis of population presence at a site of interest.

2.6. Ranking of Vulnerability Centers

The identification and the detailed analysis of all the vulnerability centers around a site where a major accident hazard is present is a time-consuming and a cumbersome issue. Each center x should be reported on a map. Its position and its area, A_x, may be easily retrieved from aerial photos. The number of persons N_{ix} of each population category present should be estimated. In general, this information may not be available to public authorities. In some Italian studies,[25,36,47] telephonic interviews to managers of each vulnerability center were necessary to obtain such data. Thus, the availability of preliminary screening criteria to understand which vulnerability centers need to be considered in a specific context is an important tool to simplify the analysis.

In the framework of emergency planning, a ranking of vulnerability centers should be on the basis of the maximum number of persons who may be present, on their mobility, health status, and condition. Attention has to be focused first of all on the centers where unusually vulnerable population categories are present, such as young children or elderly people, infirm or disabled persons, convicts, foreigners, and so on. After an accident, the emergency services need to address first of all these sites.[37] Thus, in the framework of emergency planning, vulnerability centers may be divided in two groups: (i) vulnerability centers where at least one population category has a limited mobility or a poor health state; and (ii) vulnerability centers where no population categories with limited mobility are present. The vulnerability centers belonging to the first group were indicated in italic in Table II.

In the framework of QRA, the importance of vulnerability centers is related to the number of persons who may be affected by the adverse consequences of an accident. The first approach to this problem is to calculate the total number of simple equivalent residents present in the xth vulnerability center, $SNRT_x$:

$$SNRT_x = \sum_{i=1}^{N_{\mathrm{pc},x}} SEC_{\mathrm{Res},i} \cdot N_{i,x}, \qquad (4)$$

Table V. Equivalency Data Among Different Population Categories: Values of the Simple Equivalence Coefficient $SEC_{Res,i}$ and of the Quadratic Equivalence Coefficient $QEC_{Res,i}$; Number of Residents Equivalent to 100 Persons Belonging to the ith Population Category Calculated by the Simple (SNR_{100-i}) and the Quadratic Criterion (QNR_{100-i}); Number of Persons Belonging to the ith Population Category Equivalent to 100 Residents Calculated by the Simple ($SN_{i,100-Res}$) and the Quadratic ($QN_{i,100-Res}$) Criterion[52]

	Population Category$_j$	$PP\%_{AV,i}$ Eulerian Approach	$SEC_{Res,i}$	$QEC_{Res,i}$	SNR_{100-i}	QNR_{100-i}	$SN_{i,100-Res}$	$QN_{i,100-Res}$
P01	Patients	100	1.77	1.33	177	133	56	75
P71	Industry shift workers	88.5	1.57	1.25	157	125	64	80
P15	Residents	56.5	1.00	1.00	100	100	100	100
P16	Customers	46.5	0.82	0.91	82	91	122	110
P02	Shift workers (health service)	39.3	0.70	0.83	70	83	143	120
P71	Industry daytime workers	21.1	0.37	0.61	37	61	270	164
P08	Scholars (primary school)	17.4	0.31	0.55	31	55	323	182
P50	Spectators (stadium)	1.0	0.02	0.13	2	13	5,000	7,692

where $N_{pc,x}$ is the number of population categories present in the xth vulnerability center. Clearly enough, the total number of equivalent residents is a significant quantity to be used in risk analysis because it gives the equivalent number of residents who may be affected by an accident from a merely probabilistic point of view. However, the above criterion does not consider that the number of persons simultaneously present in a vulnerability center may be very high even if the average probability of presence is low (e.g., in the case of a stadium). Thus, assessing the importance of a vulnerability center only on the basis of the equivalent number of residents may lead to underestimating the importance of some vulnerability centers.

To overcome this problem, it is useful to define also a "quadratic" resident equivalence coefficient. This may be used to rank the criticality of vulnerability centers with respect to societal risk issues and to emergency planning. The quadratic equivalence coefficient for the ith population category may be defined as:

$$QEC_{\text{Res},i} = \sqrt{\frac{PP\%_{\text{AV},i}}{PP\%_{\text{AV,Res}}}}. \tag{5}$$

The definition of the quadratic equivalent coefficient may be derived from the risk aversion criterion underlying the definition of societal risk acceptability rules. This criterion, adopted in the Netherlands since 1978, recognizes that risk tolerability should be lower for accidents involving a higher number of fatalities.[54] In fact, the Dutch acceptability criterion for societal risk deriving from "Seveso" installations (i.e., sites falling under the obligation of the "Seveso" Directives[1–3]) requires the cumulated frequency F to be lower than $10^{-3}/N^2$, where N is the number of fatalities. Criteria similar to the quadratic approach are also proposed in the United Kingdom to assess different societal "risk integral" parameters, that is, overall risk indicators calculated from F/N plots.[55]

The quadratic equivalence coefficient may be used to calculate a quadratic number of equivalent residents, defined as:

$$QNR_{i,x} = QEC_{\text{Res},i} \cdot N_{i,x}. \tag{6}$$

In analogy with Equation (4), the total number of quadratic equivalent residents $QNRT_x$ present in the xth vulnerability center may be calculated as:

$$QNRT_x = \sum_{i=1}^{N_{pc,x}} QEC_{\text{Res},i} \cdot N_{i,x}. \tag{7}$$

Table V shows the quadratic equivalence coefficient and the number of quadratic equivalent residents corresponding to 100 persons of the category of interest, QNR_{100-i}, calculated for some population categories.

For each population category it is interesting to calculate also the simple and quadratic number of persons belonging to category i that are equivalent to 100 residents (defined, respectively, as $SN_{i,100-\text{Res}}$ and $QN_{i,100-\text{Res}}$). These numbers yield an equivalency threshold for each population category referred to resident population. Table V shows that such thresholds may be very different. On one hand, population categories having high presence probabilities show equivalence coefficients lower than 100. On the other hand, population categories having very low presence probabilities show equivalence coefficients even two orders of magnitude higher than 100.

The analysis of Table V evidences that simple and quadratic resident equivalence coefficients provide easy and sound criteria to estimate the number of equivalent residents in each vulnerability center. The approach based on the calculation of the equivalent number of residents allows the comparison of vulnerability centers, either using threshold criteria or an absolute ranking based on population presence. The simple resident equivalence coefficient provides a ranking criterion based on risk equivalency, whereas the quadratic equivalence coefficient also takes into account risk aversion issues.[54–56]

It is important to recall that in this study the quadratic approach is proposed only to define an equivalency criterion among vulnerability centers. The criterion is not suitable for societal risk calculation or for the numerical calculation of F/N curves. The only correct values of the points of an F/N plot are those obtained considering the actual number of persons present in a center and their presence probability.

2.7. Cut-Off Values for Vulnerability Centers

As discussed earlier, obtaining detailed information on vulnerability centers and implementing them into a GIS-based risk assessment software is a cumbersome procedure. Usually, a very high number of vulnerability centers may be present in a district. Therefore, when the analysis of an extended area is undertaken, a relevant problem is the definition of a sound "cut-off" value: a threshold value below which the presence of the center may be neglected and/or assimilated to the average population presence in the area.

A further problem emerges from the population density in the vulnerability center. It may occur that in a crowded urban area vulnerability centers do not have population densities much different from those of the "background" resident population, and thus may be assimilated to the nearby residential area without introducing relevant errors in risk assessment. However, in industrial areas where no resident population is present, even vulnerability centers having low densities of nonresident population may be important to consider. Thus, cut-off values need to be defined also taking into account the density of resident population in the area. If a vulnerability center where only resident population is present ("P15-Residents") is considered, a cut-off value may be defined as:

$$CutOff_{\mathrm{Res},x} = DenRes_x \cdot A_x, \tag{8}$$

where $DenRes_x$ is the density of residents in the zone where the xth vulnerability center is sited and A_x is the area occupied by the center. The cut-off value introduced by Equation (8) is the value below which the vulnerability center will give the same or even less contribution to risk calculations than the background population in the area. Thus, it may be reasonably neglected in risk calculations, assuming that only resident population is present.

Starting from Equation (8), the equivalence coefficients reported in Table V may be used to calculate cut-off values for other categories of population:

$$CutOff_{i,x} = \frac{1}{\max\left(SEC_{\mathrm{Res},i},\, QEC_{\mathrm{Res},i}\right)} \cdot CutOff_{\mathrm{Res},x}. \tag{9}$$

In Equation (9) the definition of conservative cut-off values suggests to choose the lowest value obtained using the simple and quadratic equivalence coefficient. Combining Equations (8) and (9), the following expression is obtained:

$$CutOff_{i,x} = \frac{1}{\max\left(SEC_{\mathrm{Res},i},\, QEC_{\mathrm{Res},i}\right)} DenRes_x \cdot A_x. \tag{10}$$

If more than a single category of population is present in a vulnerability center, the overall cut-off value for the vulnerability center may be calculated as:

$$CutOff_x = \frac{\sum_{i=1}^{N_{\mathrm{pc},x}} N_{i,x}}{\sum_{i=1}^{N_{\mathrm{pc},x}} N_{i,x} \cdot \max\left(SEC_{\mathrm{Res},i},\, QEC_{\mathrm{Res},i}\right)} \cdot DenRes_x \cdot A_x. \tag{11}$$

Although the values of $DenRes_x$ may be easily retrieved from census data available for the site of interest, information about the area occupied by a center should be derived from specific data or from the elaboration of aerial photos. If no data are available, a default value of 1 ha can be assumed for A_x because several case studies have evidenced that this is a significant reference value for the mean extension of vulnerability centers.[47]

The cut-off values estimated for some population categories are presented in Table VI. These were calculated for different residential population densities taken from the literature,[33] ranging from 1 person/ha (a nearly inhabited area) to 200 persons/ha (a densely populated residential area). The value of 1 ha was assumed for A_x. As shown in the table, differences up to three orders of magnitude are present in the cut-off values depending on the density assumed for the background resident population. These results evidence that threshold criteria need to be

Table VI. Cut-Off Values for Some Population Categories Evaluated by Equation (11) Considering Different Values of the Density of the Residential Population and Assuming the Surface Area of the Vulnerability Center, A_x, Equal to 1 ha[52]

$DensRes_x$ (persons/ha)⇒		1	5	10	50	100	150	200
Population Category (*i*)⇓		$CutOff_{i,x}$ (persons)						
P01	Patients	1	4	8	38	75	113	150
P71	Industry shift workers	1	4	8	40	80	120	160
P15	Residents	1	5	10	50	100	150	200
P29	Guests (hotel)	0	2	4	18	35	53	71
P16	Customers	1	6	12	61	122	183	244
P40	Audience (cinemas)	1	4	7	36	72	107	143
P70	Industry daytime workers	3	13	27	134	268	402	536
P08	Scholars (primary school)	3	16	32	162	325	487	649
P18	Students (high school)	1	7	13	66	132	197	263
P44	Audience (open air cinemas)	7	33	67	334	668	1,002	1,336
P52	Spectators (arenas)	9	45	90	451	902	1,353	1,804
P50	Spectators (stadium)	57	283	565	2,825	5,650	8,475	11,300

defined taking into account the population density in the area.

The numerical values of cut-off thresholds shown in Table VI are based on the specific average presence probabilities reported in Table II. However, the methodology for their calculation has a general validity and can be applied also using different input data.

As stated above, the $CutOff_x$ value represents the value of the equivalent number of residents above which the vulnerability center should be considered separately from the background. In a QRA framework, the average population density of the surroundings may be assumed for a center that falls below the cut-off value.

In emergency planning, among the vulnerability centers without susceptible population, priority should be given to those having a higher difference among the actual population present and the cut-off value.

Thus, the above defined cut-off criteria are important in the identification of relevant vulnerability centers both in risk assessment and emergency planning.

It is interesting to compare the above cut-off criteria with previous attempts to rank vulnerability centers based on expert judgment. A significant example may be the Italian Ministerial Decree regulating LUP with respect to major accident hazards.[42] This regulation classifies the land use around major hazard installations into six categories (as reported in Table VII) both on the basis of a specific value of the building index (BI) and of the presence of vulnerability centers identified using cut-off values. The Decree does not define a cut-off value for resident population but defines cut-off values for customers of shopping malls. Thus, to assess the consistency of the cut-off values proposed by the Decree, a simple equivalence coefficient of the ith population category referred to the category "P16-Customers" (Table II) was defined as follows:

$$MD{-}SEC_{Cst,i} = \frac{MD{-}CO_i}{MD{-}CO_{Cst}}, \qquad (12)$$

where $MD\text{-}CO_i$ and $MD\text{-}CO_{Cst}$ are the cut-off values introduced by the Decree, respectively, for the ith population category and the category "P16-Customers." Table VIII shows a comparison of the values obtained by Equation (12) with those calculated starting from data in Table VII (respectively, $SEC_{Cst,i}$ and $QEC_{Cst,i}$, calculated by Equations (3) and (5) using the data on presence probabilities available in this study).

The table shows that the $MD\text{-}SEC_{Cst,i}$ equivalence coefficients are different from both the simple and the quadratic equivalence coefficients. Moreover, the values of $MD\text{-}SEC_{Cst,i}$ do not decrease with the decrease of the mean presence probability of the ith population category. The lack of internal coherency evidenced by the figures introduced by the Decree highlights the potential importance of the equivalence criteria discussed above, which are able to provide a transparent and sound guidance to support technical decisions concerning land use and emergency planning.

Table VII. Categories of Land Use Around Major Hazard Installations Adopted in Italy[42]

Territorial Category	Category A	Category B	Category C	Category D	Category E	Category F
Value of the Building Index (BI) OR	Res. area $BI > 4.5\ m^3/m^2$	Res. area $1.5 < BI < 4.5\ m^3/m^2$	Res. area $1.0 < BI < 1.5\ m^3/m^2$	Res. area $0.5 < BI < 1.0\ m^3/m^2$	Res. area $BI < 0.5\ m^3/m^2$	
Presence of a vulnerability center		Number of persons		Only vulnerability centers with aggregation frequency lower than 0.083 events/year authorized	Only industrial activities, farms, or animal husbandries authorized	Separation area—should be clear of houses or any other building
C01 Hospitals	>25	<25	–			
C08 Primary schools	>100	<100	–			
C17 Supermarkets	–	>500	<500			
C20 High schools	–	>500	<500			
C29 Hotels (all year open)	–	>500	<500			
C43 Sports stadia	–	>100	<100			
C40 Open-air cinemas	–	>100	<100			
C44 Indoor sports arenas	–	>1,000	<1,000			
C38 Indoor cinemas	–	>1,000	<1,000			

Table VIII. Equivalence Coefficients and Cut-Off Values: Comparison of the Calculated Values with Those Obtained from the Italian Ministerial Decree on LUP[42]

					Equivalence Coefficients		
Population Category$_i$		$PP\%_{AV,i}$	Range of $Cut\ Off_{i,x}$	$MD\text{-}CO_i$	*Simple* $SEC_{Cst,i}$	*Quadratic* $QEC_{Cst,i}$	*Min.Decree* $MDSEC_{Cst,i}$
P01	Patients	100.0	1–150	25	0.47	0.69	0.05
P29	Guests (hotel)	51.0	0–71	500	0.91	0.95	1.00
P16	Customers	46.6	1–244	500	1.00	1.00	1.00
P40	Audience (cinemas)	25.2	1–143	1,000	1.85	1.36	2.00
P08	Scholars (primary school)	17.4	3–649	100	2.68	1.64	0.20
P18	Students (high school)	13.7	1–263	500	3.40	1.84	1.00
P44	Audience (open-air cinemas)	2.7	7–1,336	100	17.26	4.15	0.20
P52	Spectators (arenas)	2.0	9–1,804	1,000	23.30	4.83	2.00
P50	Spectators (stadium)	1.0	57–11,300	100	46.60	6.83	0.20

3. VALIDATION BY CASE STUDIES

3.1. Presentation of the Case Studies

Two case studies were used to validate the proposed methodology.

The first was on the basis of the available data of the industrial area of Livorno, in Italy. Livorno is located on the Tyrrenian coast and around its commercial harbor a relevant industrial area has developed. Several sites falling under the obligations of the "Seveso" Directives[1–3] are present in the area. As a consequence, there is a relevant flow by ship, pipeline, road, and rail of hazardous materials (both flammable and toxic) from and to the industrial area. A quantitative risk analysis is available for the area,[47,48] which includes risk sources due to storage, process plants, and transportation of hazardous materials.

In the present case study, only the road and rail transport of hazardous substance was considered because roads and rails of concern cross densely populated suburbs. Details on the annual flow of hazardous materials by road and rail and on the possible accident scenarios and final outcomes are listed in Table IX. Table X reports the accident frequency and the release probability considered in the analysis, as well as the characterization of the loss of containment (LOC) events assumed for the road tankers and the railcars. The same occurrence probabilities of the final outcomes have been assumed for road tankers and railcars, as reported in Table XI. Available meteorological data allowed to consider

Table IX. Case Study 1: Hazardous Materials Flow by Road and Rail and Possible Final Outcomes[47,48]

Substance	Hazardous Materials Flow: Road Tankers/Year	Hazardous Materials Flow: Railcars/Year	Final Outcomes
Hydrogen chloride	210	–	Toxic cloud
Flammable liquids	76,594	1,931	Poolfire
LPG	31,489	1,503	Jetfire, fireball, VCE, VCF
Methanol	1,620	–	Poolfire, toxic cloud
Acrilonytrile	–	30	Poolfire, toxic cloud
Chlorine	–	1,274	Toxic cloud

Table X. Case Study 1: Characterization of the Loss of Containment Events of Road Tankers and Railcars[47,48]

Road Transport			
		Atmospheric road tanker	Pressurized road tanker
Accident frequency		6.7×10^{-7} events/year/vehicle	
LOC type			
Release probability	Hole	0.13	0.05
	Catastrophic rupture	0.0015	0.0005
Equivalent diameter	Hole	50	30
	Catastrophic rupture	–	–
Rail Transport			
		Atmospheric railcar	Pressurized railcar
Accident frequency		5.0×10^{-8} events/year/vehicle	
LOC type			
Release probability	Hole	0.08	0.03
	Catastrophic rupture	0.002	0.005
Equivalent diameter	Hole	50 mm	30 mm
	Catastrophic rupture	/	/

three Pasquill atmospheric stability classes and three corresponding wind speed values for consequence assessment: B-1.5 m/s, D-4 m/s, and F-1.6 m/s. Available statistical data were used for probability of wind direction.

Information about the distribution of resident population was derived from the national census.[53] Population was represented using more than 850 polygons with variable surface area and a density ranging from 0.05 persons/ha to 500 persons/ha. A door-to-door survey led to the identification of 194 vulnerability centers. The position and the extension of each center were derived from the analysis of the aerial images of the zone, whereas information about the number of persons of each population category present in the vulnerability centers was obtained by telephonic interviews. Fig. 1 shows the map of the area of Livorno, evidencing the road network and the railway lines considered as risk sources. The resident population distribution and the location of the vulnerability center are also reported.

The second case study refers to a more simple test area defined to explore specific issues related to vulnerability centers. Fig. 2 shows the test area, which consists in a linear risk source horizontally crossing a rectangular area where a uniform density of resident population was assumed (14 persons/ha). Different shipments of hazardous materials were considered: a flow either of 2,800 road tankers/year of LPG or of 640 railcars/year of chlorine. The same LOC categories, accident frequency, release probabilities, and occurrence probabilities of the final outcomes used in the area of Livorno were assumed (Tables IX and X). A uniform probability of wind direction was assumed, although the same three Pasquill atmospheric stability classes and corresponding wind velocity values used in the area of Livorno were considered for consequence assessment. Different types of vulnerability centers were considered in the case study. Each center was represented on the map either as a point or as a rectangle. Vulnerability centers were positioned at a distance of 320 m from the risk source.

For both case studies the consequence analysis of the various final outcomes was performed with standard consequence analysis models[57] and software tools.[58] The calculation of the societal risk indexes was performed using the ARIPAR-GIS

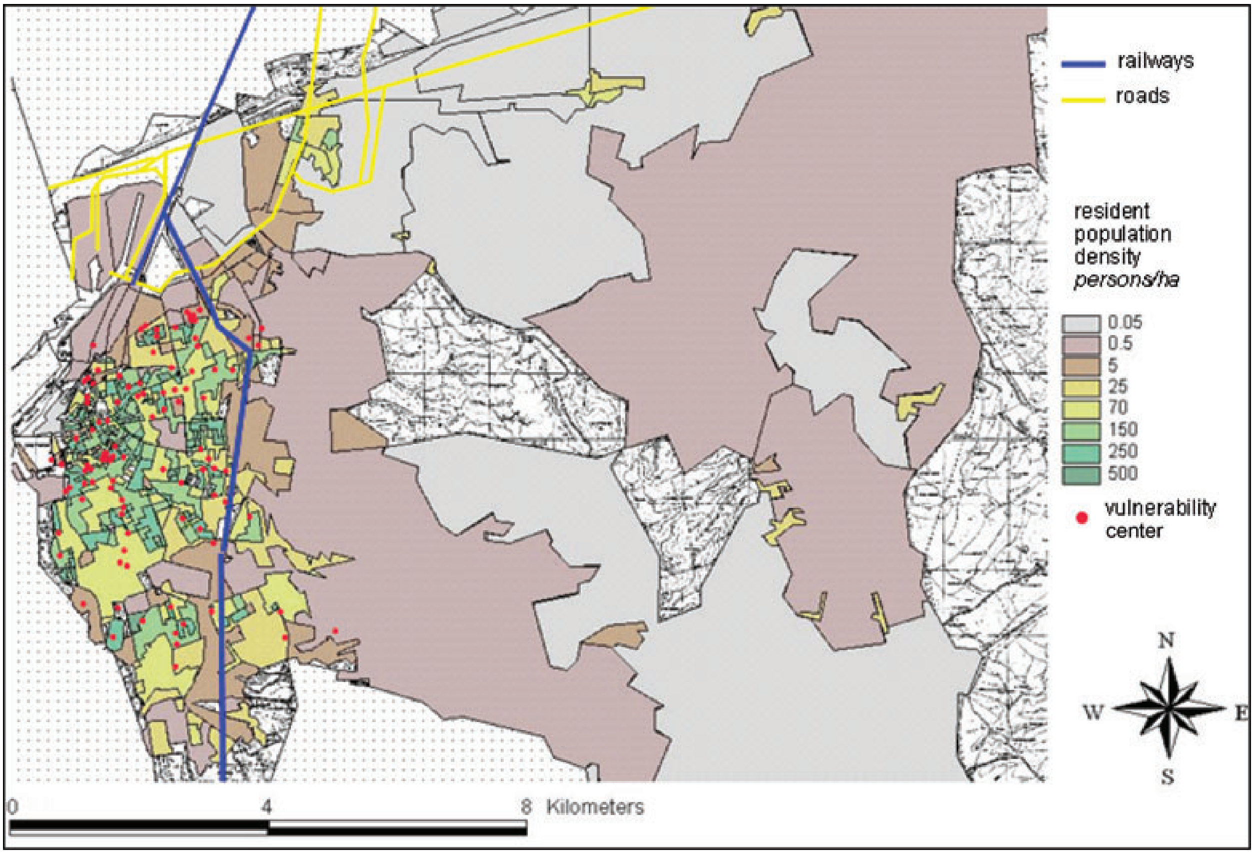

Fig. 1. Case study 1: map of the area of Livorno.

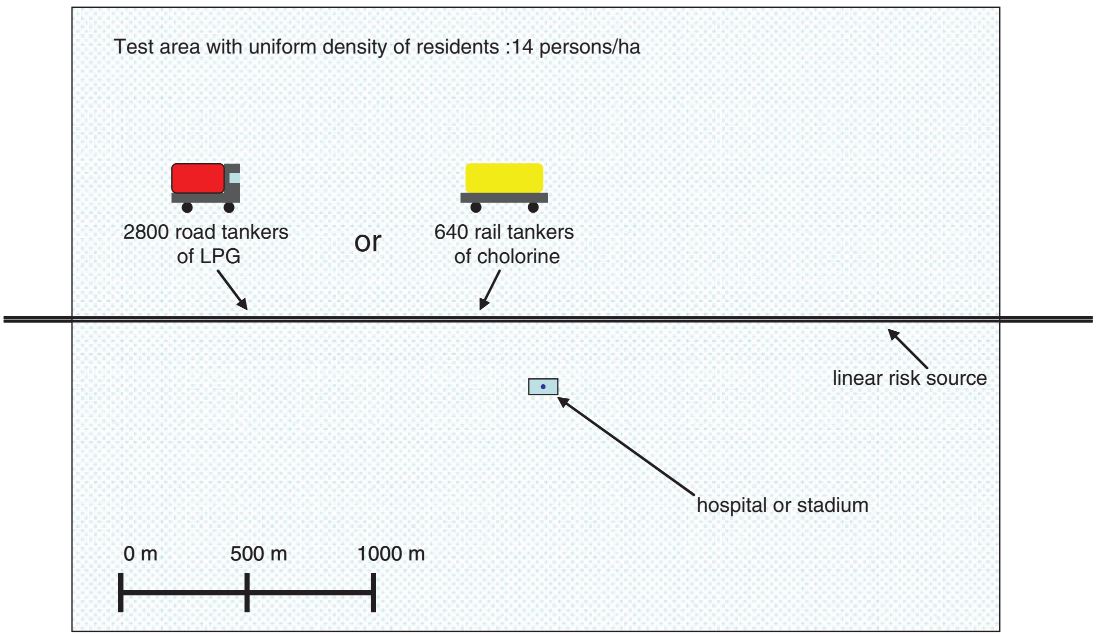

Fig. 2. Case study 2: map of the test area.

software.[26,35] The software calculates the death probability as a function of the distance from the risk source using probit models for human vulnerability[34] and the output of consequence analysis models. Overlapping the maps of the death probabilities with data on population distribution, the number of fatalities is calculated for each final outcome. The software then combines the occurrence frequencies and the calculated fatalities to obtain the *F*/*N* curve. Further details on the ARIPAR-GIS software are reported elsewhere.[59]

3.2. Results and Discussion

Fig. 3 shows the results obtained for the area of Livorno. The application of the cut-off thresholds by Equation (11) evidenced that only 97 centers of 194 (i.e., less than half) are above the threshold value. Societal risk calculations were carried out using three different assumptions: (1) all 194 vulnerability centers were considered; (2) only the 97 centers above the cut-off value were considered; (3) vulnerability centers were not considered at all. The *F*/*N* curves and the overall number of expected fatalities *E*[60] calculated for the three cases considered are reported in Fig. 3.

On one hand, Fig. 3 evidences that the contribution of vulnerability centers to societal risk is high. As a consequence, neglecting them in a risk analysis implies an important underestimation of risk. The difference in *E,* when ignoring vulnerability centers, is higher than one order of magnitude. If the *F*/*N* curve is considered, for some values of *N* the difference in *F* is as high as five orders of magnitude. On the other hand it may be remarked that both the *F*/*N* curves and the values of *E* calculated considering only the 97 centers above the cut-off values are almost coincident with the results obtained taking into account all 194 centers: this confirms the validity of the proposed cut-off criterion for vulnerability centers.

Fig. 4 shows some results obtained for the second case study. In the figure, the *F*/*N* curves obtained considering the vulnerability centers “C01-Hospital” and “C50-Stadium” are shown because these centers are characterized, respectively, by the maximum and minimum value of the presence probability. Figs. 4(a) and (b) clearly show that in the case of scenarios involving the dispersion of toxic compounds in the atmosphere, the modality of representation of vulnerability centers has a scarce influence. On the other hand, when fire scenarios are of concern, the punctual representation of vulnerability centers results in a more conservative estimation of risk, as shown in Figs. 4(c) and (d). The final outcomes related to flammable substances have minor impact distances compared to those produced by toxic scenarios. Thus, risk values are more sensitive to changes in vulnerability. Furthermore, in the case of some fire scenarios, risk suddenly decreases with the distance from the risk source: for example, in the case of a flash fire where the probability of death is assumed as negligible outside the flammable cloud. Thus, when a vulnerability center is represented by an area, if a zone falls outside the impact area of the scenario, it involves a negligible contribution to risk. Similar results, not reported for the sake of brevity, were obtained considering other types of vulnerability centers and varying both the density of residents and the distance of the centers from

Table XI. Case Study 1: Occurrence Probabilities of the Final Outcomes[47,48]

LOC Type	Final Outcomes	Atmospheric Road Tanker or Railcar	Pressurized Road Tanker or Railcar
Hole	Poolfire	0.15	–
	VCF	–	0.35
	VCE	–	0.20
	Toxic cloud (methanol, acrylonitrile)	0.85	0.35
	Toxic cloud (chlorine hydrogen chloride)	1	1
	Jetfire	–	0.20
Catastrophic rupture	Poolfire	0.15	–
	VCF	–	0.50
	VCE	–	0.13
	Toxic cloud (methanol, acrylonitrile)	0.85	0.35
	Toxic cloud (chlorine hydrogen chloride)	1	1
	Fireball	–	0.20

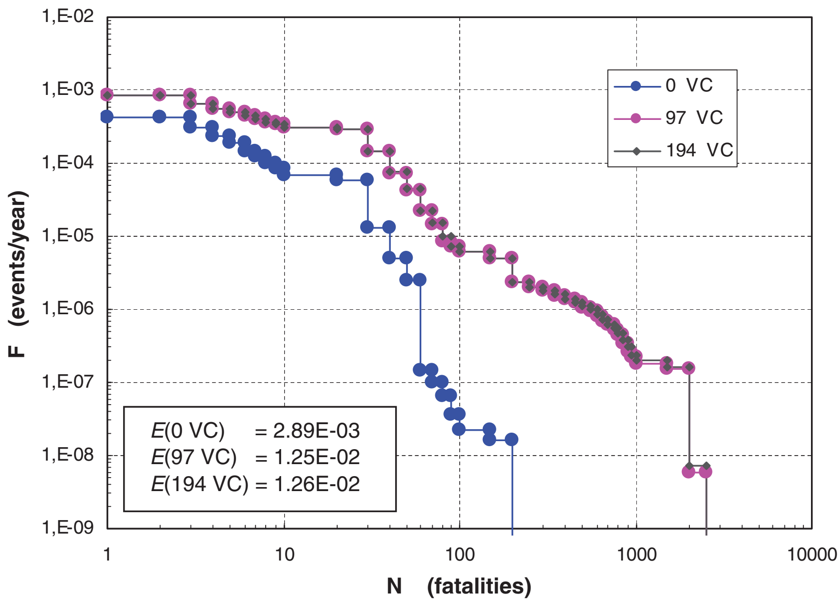

Fig. 3. Case study 1: contribution of vulnerability centers (*VC*) to societal risk (*E* in fatalities/year).

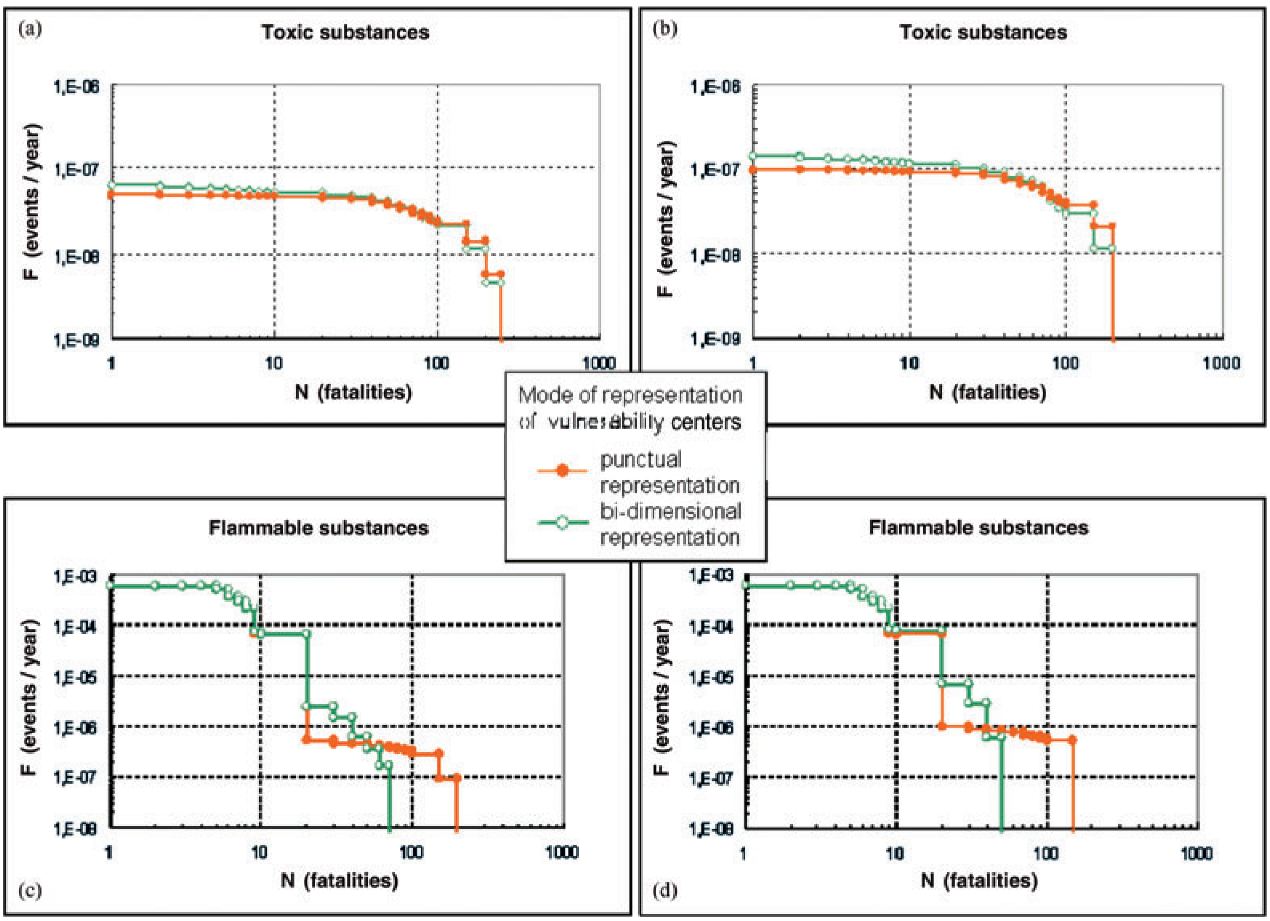

Fig. 4. Case study 2: influence on societal risk of the mode of representation of vulnerability centers: (a) transport of toxic substances, residents, and a stadium; (b) transport of toxic substances, residents, and a hospital; (c) transport of flammable substances, residents, and a stadium; (d) transport of flammable substances, residents, and a hospital.

the risk source. The above findings may thus be considered of general validity.

4. CONCLUSIONS

A methodological framework was outlined for a comprehensive description of population in QRA, land use, and emergency planning studies, with a specific focus on vulnerability centers. An extended list of vulnerability centers and population categories was defined, and plausible values of presence and indoor/outdoor probabilities were proposed. A ranking rule and equivalence criteria among vulnerability centers were established. Criteria to define scientifically sound cut-off values for the census of vulnerability centers were proposed. The application of the outlined approach to some case studies confirmed the validity of the proposed cut-off criteria.

APPENDIX

A_x: area occupied by the xth vulnerability center.

$CutOff_{i,x}$: cut-off value for the ith population category (number of persons) in the xth vulnerability center.

$CutOff_{\mathrm{Res},x}$: cut-off values for population category "P15-Residents" (number of persons) in the xth vulnerability center.

$CutOff_x$: cut-off value for the xth vulnerability center (number of persons).

$DenRes_x$: density of residents in the zone where the xth vulnerability center is sited.

E: yearly expected number of fatalities (number of fatalities/year).

F: cumulated frequency (events/year).

F_j: ratio of the duration of time period j over one year.

ID code: identification code of vulnerability centers and population categories.

$MD\text{-}CO_i$: cut-off values introduced for the ith population category by the Italian Ministerial Decree on LUP.[42]

$MD\text{-}CO_{Cst}$: cut-off value for the "P16-Customers" population category introduced by the Italian Ministerial Decree on LUP.[42]

$MD\text{-}SEC_{Cst,i}$: simple equivalence coefficient of population category i to the population category "P16-Customers" introduced by the Italian Ministerial Decree on LUP.[42]

N: number of fatalities.

$N_{i,x}$: number of persons belonging to the ith population category present in the xth vulnerability center.

$N_{\mathrm{pc},x}$: number of population categories present in the xth vulnerability center.

N_{tp}: number of time periods in which the year is subdivided.

$P\mathrm{indoor}_{i,j}$: conditional probability of indoor presence of an individual belonging to population category i during time period j.

$P\mathrm{outdoor}_{i,j}$: conditional probability of outdoor presence of an individual belonging to population category i during time period j.

$PP\%_{\mathrm{AV},i}$: average presence probability (%) over the year of a member of population category i.

$PP\%_{i,j}$: probability of presence (%) of a member of population category i in the time period j.

$QEC_{\mathrm{Res},i}$: quadratic equivalence coefficient for the ith population category with respect to population category "P15-Residents."

$QEC_{Shp,i}$: quadratic equivalence coefficient for the ith population category with respect to population category "P16-Customers."

$QN_{i,100-\mathrm{Res}}$: quadratic number of persons belonging to the ith population category equivalent to 100 persons belonging to population category "P15-Residents."

$QNR_{i,x}$: quadratic equivalent number of residents present for the ith population category in the xth vulnerability center.

QNR_{100-i}: quadratic number of residents equivalent to 100 persons belonging to population category i.

$QNRT_x$: total number of quadratic equivalent residents present in the xth vulnerability center.

$SEC_{\mathrm{Res},i}$: simple equivalence coefficient for ith population category with respect to population category "P15-Residents," defined as the number of residents equivalent to 1 person belonging to population category i.

$SEC_{Shp,i}$: simple equivalence coefficient for ith population category with respect to population category "P16-Customers."

$SN_{i,100-\mathrm{Res}}$: simple number of persons belonging to the ith population category equivalent to 100 persons belonging to population category "P15-Residents."

$SNR_{i,x}$: simple number of equivalent residents for the *i*th population category present in the *x*th vulnerability center.
SNR_{100-i}: simple number of residents equivalent to 100 persons belonging to population category *i*.
$SNRT_x$: total number of simple equivalent residents present in the *x*th vulnerability center.
VC: vulnerability center.
VCE: vapor cloud explosion.
VCF: vapor cloud fire.

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