Journal of Hazardous Materials A136 (2006) 170–180

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Application of land-use planning criteria for the control of major accident hazards: A case-study

Valerio Cozzani [a], Riccardo Bandini [b,1], Claudia Basta [c], Michalis D. Christou [d,*]

[a] Dipartimento di Ingegneria Chimica, Mineraria e delle Tecnologie Ambientali, Università di Bologna, viale Risorgimento no. 2, 40136 Bologna, Italy
[b] Dipartimento di Ingegneria Chimica, Chimica Industriale e Scienza dei Materiali, Università di Pisa, via Diotisalvi no. 2, 56126 Pisa, Italy
[c] DIRC Sustainable Urban Areas, Section of Material Science and Sustainable Construction, Delft University of Technology, Stevinveg 1, 5048 GA Delft, The Netherlands
[d] Major Accident Hazard Bureau, IPSC, European Commission Joint Research Centre, 21020 Ispra (VA), Italy

Received 1 March 2005; received in revised form 7 December 2005; accepted 13 December 2005
Available online 17 February 2006

Abstract

Land-use planning (LUP) with respect to major accident hazards is one of the more important requirements of Directive 96/82/EC (the so-called Seveso II Directive). Different approaches were developed by the Member States of the European Union in order to implement this aspect of the Directive. This study focuses on the comparison of the specific approaches developed for LUP with respect to major accidents hazards. An Italian industrial area has been selected to perform a case study. The different LUP criteria have been used both to evaluate the present state of the area and the effect of several proposed hazard reduction actions. The results obtained have allowed a comparison of the different LUP methodologies. Critical steps in the application of the different LUP criteria have been identified, and the different priorities of hazard reduction actions resulting from risk-based and consequence-based approaches have been highlighted.

Keywords: Land-use planning; Quantitative area risk assessment; Industrial hazards; Seveso Directives; Control of major accident hazards

1. Introduction

In recent years, a growing concern is aroused in the population about the hazards deriving from industrial sites neighbouring residential areas. Accidents as those of Bhopal and Mexico city, and more recently of Enschede and Tolouse, have clearly demonstrated how the consequences of industrial accidents may be severely amplified by the adjacency of hazardous installations and high-density population areas.

The need of land-use regulations around hazardous installations was one of the factors leading to the revision of Directive 82/501/EEC (the Seveso Directive) [1]. In the resulting Directive 96/82/EC [2] the European Commission has considered the introduction of land use planning (LUP) requirements in the vicinity of sites falling under the obligations of the Directive as a necessary measure for the mitigation of consequences of major accidents [3,4]. Thus, Article 12 of the so-called Seveso II Directive requires the Member States to introduce LUP criteria in their legislation [2]. The recent amendment of the Directive (Directive 2003/105/EC), has furthermore stressed the need to develop common guidelines, calling for the development of a common database, to be used in order to assess the compatibility between the establishments and their surroundings [3]. The deadline for the elaboration of the guidelines is the end of 2006. The renovated European Working Group on land-use planning, composed by representatives of the Competent Authorities and appointed by the Joint Research Centre of the European Commission, is currently developing this objective.

Up to now, also in the light of the recent enlargement of the European Community, a limited number of European countries have developed specific criteria for LUP with respect to major accident hazards. In the majority of them the control of land use planning in the vicinity of hazardous installations is still performed by non-specific legislation, and the risk is not explicitly considered within the land use policies [5–9]. From this point of view, the implementation of Article 12 of Directive 96/82/EC

* Corresponding author. Tel.: +39 0332 789516; fax: +39 0332 789007.
E-mail address: michalis.christou@jrc.it (M.D. Christou).
[1] Present address: STI-ENI Group, via Mazzini 12, 56125 Pisa, Italy.

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doi:10.1016/j.jhazmat.2005.12.031

requires to the Member States the elaboration of tools connecting two traditionally independent disciplines.

The principle behind LUP is that incompatible activities, such as handling of dangerous substances and residential areas, should be separated by sufficient distances. These distances should be proportional to the level of risk confronted by the receptors. For that reason, and according to Article 12 of the Seveso II Directive, it is necessary to assess the level of risk remaining after the safety measures have been applied in the installation (*residual risk*). Although it is agreed that risk is the likelihood of occurrence of unwanted consequences from an accident (see for example the definition in the Seveso II Directive), the methods for addressing this risk vary among the different countries, due to different cultural and historical background and administrative frameworks. From the methodological point of view, a few countries have adopted simplified criteria based on "safety distances" between residential areas and industrial sites [10–12]. Among the countries using more structured criteria, the literature developed in the past decade agrees with the definition of two alternative methodological approaches [10]:

(i) The consequence-based approach, focusing the assessment of the consequences of a number of conceivable scenarios (reference scenarios). Damage thresholds values for accident physical effects (toxic concentration, thermal radiation, overpressure) are determined with respect to undesired consequences (fatalities, irreversible effects, reversible effects, etc.). The method has generally been used in France,[1] and it has been adopted by other countries [3,7,13].

(ii) The risk-based approach, focusing the assessment of both consequences and expected occurrence frequency of the possible accident scenarios. The results are represented by risk indexes, in some cases both as individual risk and societal risk [7]. LUP criteria are based on specific acceptability criteria with respect to the calculated risk indexes. This approach is followed in the United Kingdom (although for certain cases the hazard assessment approach has been followed) and in the Netherlands [14–18].

More recently, Italy has adopted an hybrid criterion that takes into account the frequencies as a mitigation factor for the damage zones, identified using a consequence-oriented approach. The DM Maggio 2001 [19], implementing the national adoption of the Directive Seveso II with respect to the LUP issue, requires the identification of four degrading damage zones. From the inner "high lethality" to the outer "reversible damage" zone, threshold values for each of the three accidental cases (release, fire and explosion) are fixed by law and legally binding. The frequency values calculated for each scenario are considered as mitigating factors for LUP restrictions. Although the Italian legislation was somehow inspired by the English and Dutch regulations, it does not require the evaluation of the individual and societal risk [19,20].

Clearly, all around Europe different and sometimes apparently conflicting approaches have been adopted for LUP with respect to major accident hazard. The aim of the present paper is to compare the results of the application of the different criteria to an existing industrial area. The final objective is to identify the land-use restrictions imposed by the different criteria and to underline which types of hazard reduction actions are prioritary in the different approaches. An Italian industrial area, the zone of Piombino, has been chosen for the study. In this area a quantitative area risk assessment (QARA) study was promoted in 1998. Complete information is available both on hazardous installations and on the transport of hazardous goods. On the basis of the results of the QARA study, the local authorities proposed several hazard reduction actions. The different LUP criteria are applied both to the present situation and to the situation after the hazard reduction actions.

It is worth mentioning here that the intention of the paper is not to compare countries or administrative systems, but to compare methods in a common case study. Although for simplification reasons we refer to the methods and criteria as the "French", the "Dutch" and the "Italian" methods, we actually intend the "consequence-based", the "risk-based" and a "mixed" method as they have been described in the literature. The exact application of the different methods in the particular administrative systems is usually complicated and it depends on the particular circumstances. For that reason it is out of the scope of this paper to analyse or evaluate the exact application of the methods in the particular administrative systems.

2. The industrial risk in the area of the case-study

The map of the area considered for the case-study is reported in Fig. 1. The Piombino area it is an Italian area with three industrial plants falling under the obligations of the Seveso II Directive. Two of these plants (P1 and P2) are establishments producing and processing steel, while the other (P3) is an air distillation plant. It is important to remark the proximity between

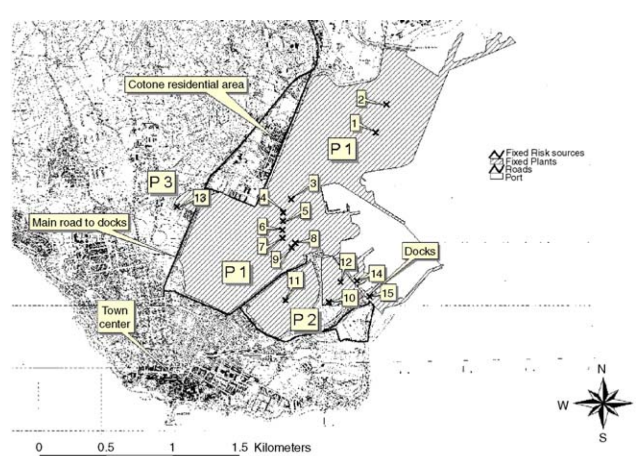

Fig. 1. The area of the case-study.

[1] Recent developments of the French legislation introduced the possibility in the future to consider frequency estimations as a tool for rationalising the scenarios to be taken into account for land-use planning.

the industrial areas and some residential districts of the town (especially the zone of Cotone), as shown in Fig. 1.

The port of Piombino also represents a very important risk source in the area. The port manages a relevant touristic traffic, consisting of more than 3,500,000 passengers/year. Furthermore, the port also faces an important commercial traffic. The commercial traffic leads to the presence of a relevant number of trucks carrying hazardous substances (in particular explosives, LPG, and gasoline). Both the touristic and commercial traffic mainly consist of vehicles loaded or unloaded from ferry boats. No storage plants are present in the port. Only seven buried diesel fuel deposits are present, for ferryboat refuelling. The docks and the loading/unloading areas are very small and in the present situation no physical buffer is present between the touristic and commercial areas of the port.

With respect to the transport of hazardous goods, these are only transported by road in the area. There is only one road that connects Piombino to the main highway leading to north or south of Italy. Thus, all the traffic directed to Piombino transits on this road. Moreover, the final part of this route runs inside the town centre and is often crowded by the local traffic, potentially leading to dangerous situations.

In order to apply and compare the different European LUP criteria, detailed information on the risk sources present in the area considered are needed. The Italian Ministry of Environment together with the Toscana Regional Authorities promoted in 1998 a QARA study of the Livorno and Piombino areas. The Piombino QARA study was coordinated by ARPAT (the Regional Environmental Protection Agency) and performed by the University of Pisa. Both the fixed risk sources and the hazards arising from the transport of hazardous substances in the area were considered. The methodology of the QARA study and the results obtained are reported elsewhere [21,22].

Thus, a detailed analysis of the risk sources present in the Piombino area was available. In order to perform the present study, the 1998 QARA study has been updated taking into account the modifications occurred to the fixed plants present in the area. The study has been upgraded using the 2.1 version of the Aripar-GIS software [23–25]. Fig. 1 shows the position of the fixed risk sources, and Table 1 reports the accidental scenarios considered in the updated QARA study [26]. Table 2 summarizes the data on the transport of hazardous substances in the area.

Fig. 2 shows the map of the individual risk in the area, obtained using the Aripar-GIS software. The societal risk in

Table 1
Data on fixed risk sources and on accidental scenarios considered (see Fig. 1 for the position of risk sources)

Source no.	Substance	Scenario	Frequency (events/year)	French method		Frequency class	Italian method			
				Z1 (m)	Z2 (m)		*R*1 (m)	*R*2 (m)	*R*3 (m)	*R*4 (m)
1	Blast furn. gas	UVCE	3.20×10^{-3}	115	250	1	35	75	150	350
2	Coke gas	UVCE	–	370	805	–	–	–	–	–
	Coke gas	Jet fire	2.04×10^{-4}	–	–	2	21	28	33	42
	Coke gas	UVCE	1.10×10^{-4}	–	–	2	45	97	193	450
3	Blast furn. gas	UVCE	–	350	760	–	–	–	–	–
	Blast furn. gas	Jet fire	2.04×10^{-4}	–	–	2	21	28	33	42
	Blast furn. gas	UVCE	1.10×10^{-4}	–	–	2	45	97	193	450
4	Coke gas	UVCE	5.00×10^{-5}	65	145	3	30	45	90	300
5	Coke gas	UVCE	5.00×10^{-5}	65	145	3	30	45	90	300
6	Coke gas	UVCE	5.00×10^{-5}	65	145	3	30	45	90	300
7	Coke gas	UVCE	5.00×10^{-5}	65	145	3	30	45	90	300
8	Blast furn. gas	UVCE	–	295	640	–	–	–	–	–
	Blast furn. gas	Jet fire	2.04×10^{-4}	–	–	2	21	28	33	42
	Blast furn. gas	UVCE	1.10×10^{-4}	–	–	2	45	97	193	450
9	Coke gas	UVCE	3.20×10^{-3}	130	285	1	35	75	150	350
10	Ammonia	Inst. release	–	1165	2140	–	–	–	–	–
11	Ammonia	Cont. release	3.03×10^{-5}	–	–	3	0	–	300	–
	Ammonia	Cont. release	1.00×10^{-8}	60	450	4	0	–	550	–
12	Ammonia	Cont. release	9.47×10^{-7}	–	–	4	0	–	25	–
13	Paints	Pool fire	4.60×10^{-4}	45	55	2	23	37	45	67
	HCl	Cont. release	4.60×10^{-4}	–	–	2	0	–	40	–
	HF	Cont. release	4.60×10^{-4}	–	–	2	0	–	75	–
14	Diesel fuel	Pool fire	4.00×10^{-9}	60	75	4	23	37	45	67
15	Diesel fuel	Pool fire	2.00×10^{-6}	60	75	3	25	28	34	45
	LPG	UVCE	1.00×10^{-6}	275	600	4	10	25	45	75
	LPG	Jet fire	1.50×10^{-6}	–	–	3	105	118	130	152
	Explosives	UVCE	5.00×10^{-7}	250	685	4	57	122	244	569

Table 2
Road transport of hazardous substances in the area of the case-study

Substance	Quantity	
	(trucks/year)	(t/year)
LPG	748	14960
Gasoline	82	1596
Diesel fuel	2500	64097
Flammable liquids	45	900
Organic solvents	20	275
Paints	320	5760
Explosives	301	8
Calcium carbide	180	4500
Hydrochloric acid	120	2550
Ammonia	30	420
Liquid oxygen	2669	58718
Liquid nitrogen	1725	37950
Liquid argon	345	7590
Total	9085	199324

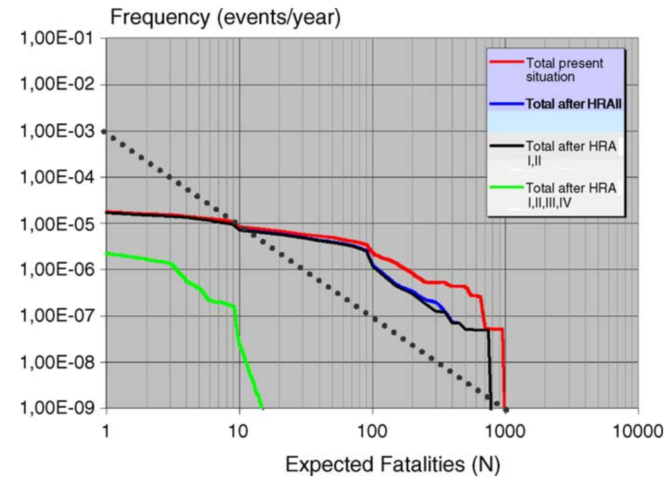

Fig. 3. Societal risk (*F–N* curves) in the area studied.

the area is represented in Fig. 3, that shows the calculated *F–N* curve. It is important to notice that the docks where the trucks are loaded on ferry boats are considered as fixed installations. Fig. 2 points out that with the used methodology the individual risk in the residential areas results generally lower than 10^{-7} events/year. Values higher than 10^{-5} events/year are present in the proximity of the industrial plants, and in a small zone between the P2 plant and the harbour area. The most important contribution to the individual risk in the residential areas is given by the road transport of hazardous substances, especially on the route directed to the industrial plants and to the port, with values comprised between 10^{-7} and 10^{-8} events/year. The societal risk (Fig. 3) shows frequency values (*F*) of about 10^{-5} events/year for *N* less than 100. The values of *F* become negligible for *N* higher than 1000.

The most important risk sources identified in the area are the docks and the process plants near to the port, also due to the high number of tourists that are exposed to the hazards.

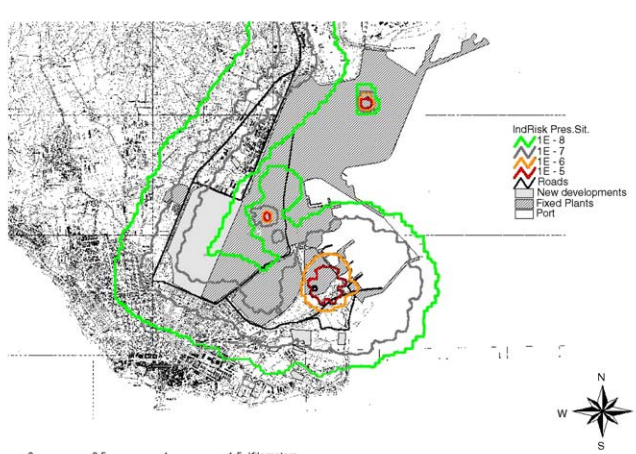

Fig. 2. Individual risk map in the present situation.

3. Application of LUP criteria

3.1. French LUP criterion

The French LUP criterion and the procedures to be followed for its application are fully described elsewhere [13]. It must be mentioned that after the accident of Toulouse, the French Competent Authority (Le Ministere de l’Ecologie et du Developpement Durable) revised the legislation on land use planning. The *Plan de Prévention des Risques Technologiques* (*PPRT*), as regulated within the new *Loi du 30 julliet 2003* does not change the principles on which the previous regulation was based (i.e. responsibility of the operators; prevention of the risk from the source, etc.). However, it tries to provide a more rational framework for land-use planning, which may use failure frequences as a tool to assess the relevance of accident scenarios for LUP. The methodology is presently under definition and therefore, the present study considers only the existing consequence-based criteria, which represent a consolidated system applied in other countries outside France (e.g. the Walloon Region of Belgium).

All the fixed risk sources shown in Fig. 1 were considered for the application of the French method. It must be remarked that the French approach does not take into account the hazards deriving from the transportation of dangerous substances in LUP. However, the risk hazards caused by the loading and unloading of hazardous materials on the ferry boats in the port docks were considered as fixed risk sources in the QARA study, and were thus considered in the analysis.

Coherently with its deterministic/effects-based approach, the application of the French criteria required the identification of the worst-case scenario for each risk source and the calculation of the damage zones. The worst-case scenarios were identified “a priori” or through the comparison of all the alternative accidental scenarios, selecting the one generating the widest damage zones. The threshold values used to calculate the protection zones were extrapolated from official documents produced by the Service de l’Environnement Industriel (SEI) [27].

The application of the French LUP criterion required the identification of two circular damage zones. The identification of

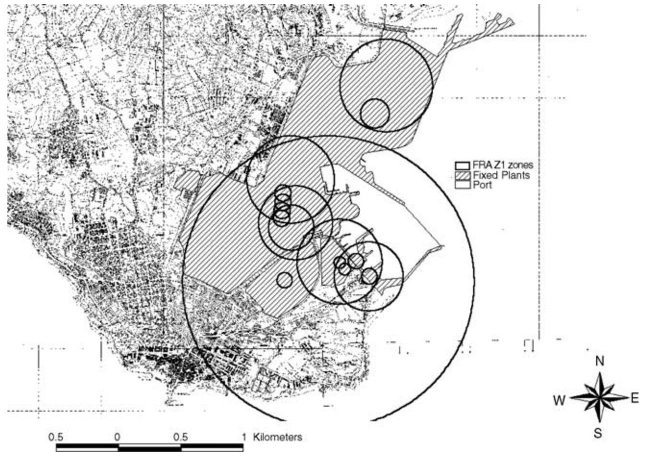

Fig. 4. Z1 protection zones identified by the application of the French LUP criterion.

these protection zones was based on legally binding endpoint values (thresholds). These endpoint values had to be applied in order to identify the inner zone, corresponding to the beginning of lethal effects (Z1 area), and the outer zone, corresponding to the beginning of irreversible effects (Z2 area). For example, in the case of an explosion generating overpressure, the inner zone Z1 is calculated as the area where the overpressure is higher or equal to the endpoint value of 140 mbar, while the outer zone Z2 is defined as the area where the overpressure is higher or equal to the endpoint of 50 mbar.

For the purposes of the present work, in order to calculate the damage zones of the different scenarios, the recommended simplifying equations commonly used in France and reported in literature were used [13]. The protection zones due to toxic releases were calculated using the SAFETI software, which allows to model both the release and the atmospheric dispersion.

Table 1 reports all the fixed risk sources considered, the worst case scenarios and the related extensions of damage zones. The calculated radii of these zones are represented by the Z1 and Z2 damage distances also reported in the table. Fig. 4 reports the position of the Z1 zones in the Piombino area. As shown in the figure, the toxic releases are the accidental scenarios that generate the most extended damage areas. In particular, the release of pressurised liquid ammonia from a tank storage located inside the P2 plant (risk source no. 10 in Table 1) creates the biggest Z1 zone in the Piombino area, that extends over several residential areas of the town. The other wide Z1 zones are generated by the UVCE scenarios caused by the possible catastrophic release of flammable gases from the atmospheric gasholders inside the P1 plant. The damage area caused by a gasholder (risk source no. 3 in Fig. 1) partially extends over the residential area of Cotone.

The Z2 zone caused by the toxic release of ammonia extends over the entire town centre. The other Z2 areas, mainly generated by catastrophic releases from the gasholders, completely include the residential area of Cotone. The Z2 zones caused by the scenarios due to loading/unloading operations and to fuel storages in the port are extended over the entire harbour area.

Thus, the application of the French criterion resulted in wide protection zones, that extend over several residential areas. A strong indication comes for the need of hazard reduction actions, limiting the quantities of the dangerous substances causing the scenarios, or removing the risk sources.

3.2. Dutch LUP criterion

The application of the Dutch criterion required the calculation of individual and societal risk. To correctly apply the Dutch LUP method, the approach to scenario selection and to risk calculation given by the “purple book” [28] should be used. In particular, the purple book reports a set of mandatory accidental scenarios associated to a set of frequency values, but states that site specific values, when available, should be preferred to the standard values. Since within the QARA study of the Piombino area an extended revision of the possible accidental scenarios and of their frequency values was carried out, the individual and societal risk calculated within the QARA study by the Aripar-GIS software were directly compared with the acceptability criteria used in the Netherlands.

The threshold value for individual risk acceptability in residential areas is 10^{-6} events/year in the Dutch approach. Fig. 2 shows that the individual risk is higher than 10^{-6} events/year only in a narrow area that extends also outside the industrial sites. An area where individual risk is higher than 10^{-5} events/year is present in the proximity of the industrial plants, where only some storehouses and the Port Authority offices are located. In the 10^{-6} area the touristic ferry-boat docks, a railway station and some road networks to the harbour area are present. This causes the societal risk curve, reported in Fig. 3, to be well above the acceptable values, due to the quite high expected frequency of possible severe accidents involving the harbour area (Fig. 3).

In conclusion, with respect to individual risk the situation is under control in all the residential areas of the town. On the other hand, the societal risk exceeds the acceptability criteria used in the Netherlands for land-use planning issues, as shown in Fig. 3, where the grey line represents the acceptability criteria. Thus, the situation is not acceptable according to the Dutch criteria for land-use planning, and the introduction of risk mitigation actions is required, mainly aimed to the reduction of the societal risk.

3.3. British LUP criterion

The LUP method used in the United Kingdom and the procedures for its application are extensively described elsewhere [16–18]. The approach is based on individual risk calculation, but the effects of the road transport of dangerous substances are not considered in the standard methodology. Nevertheless, as in the QARA approach, the risk sources due to the loading/unloading procedures in the harbour areas were considered as fixed risk sources and included in the analysis. A standardized approach is performed by HSE when applying the LUP criterion. However, also in this case the site-specific QARA results were directly compared to the acceptability criteria given in the

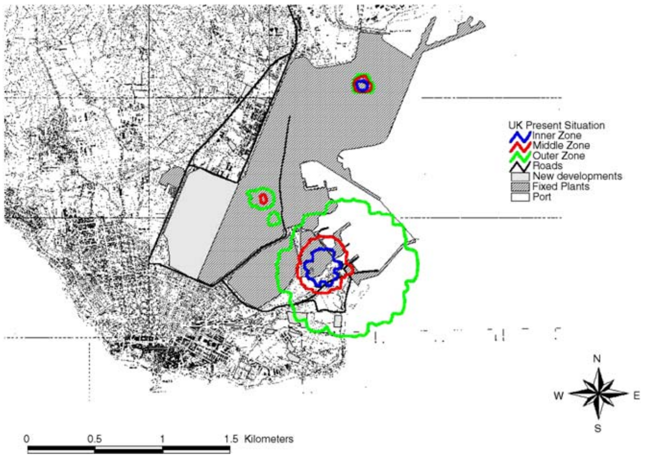

Fig. 5. Consultation zones identified by the application of the British LUP criterion.

Fig. 6. Protection zones identified by the application of the Italian LUP criterion.

method. Thus, the Aripar-GIS software was used to calculate individual risk due to the fixed risk sources.

The results, reported in Fig. 5, allowed the identification of the three consultation zones defined by the method: the inner zone (individual risk values higher than 10^{-5} events/year), the intermediate zone (individual risk values higher than 10^{-6} events/year), and the outer zone (individual risk values higher than 3×10^{-7} events/year).

The inner zone is in the proximity of the industrial plants, between the P2 plant and the harbour area. The middle zone quite well corresponds to that identified by the Dutch method, and extends over the touristic ferry-boat docks, and a railway station. The outer zone comprises the entire harbour area and two small residential areas.

In the analysis of the inner zone, no development or land-use pattern in contrast with the HSE development advice policy can be found. The situation is different for the middle and the outer zone. The port docks (about 10,000 passengers/day) are in the middle zone, and at the borders of the outer zone a retreat home for the elderly is present. According to the British criterion these development types are not advised, and a hazard reduction action is suggested.

3.4. Italian LUP criterion

No official guidelines are yet available for the application of the Italian LUP method [19]. As mentioned in the introduction, the Italian method is based on the identification, for each scenario considered, of four damage distances ($R1$–$R4$) on the basis of damage thresholds for physical effects. A probability class (comprised between $<10^{-6}$ and $>10^{-3}$ events/year) is associated to each scenario, on the basis of its calculated expected frequency. Using a matrix form, the DM Maggio 2001 [19] combines the four probability classes with the four effects areas. Each combination, representing a specific risk category, is associated to the compatible land-use categories. Since this approach requires a preliminary evaluation of the land-use patterns and of the possible environmental targets exposed to the risk, the Italian law also prescribes indicators and criteria for their assessment. Six different land-use categories are defined (from A, highly vulnerable objects/residential areas, to F, areas comprised within the boundaries of establishment). The classification of targets within each of the six categories has to be based on the use of precise indicators, referring to different criteria, depending on different kind of targets. For example, the classification of a residential building within class A, B or C is based on the index expressing the relation between built area and land surface unit, that should be related to the population density. A second example is that of hospitals, which are classified on the basis of the number of beds (>100 beds = A, <100 beds = B), since this represents the number of ill people who will need to be evacuated in the case of accident. The land-use pattern of a zone correponds to that of the more vulnerable target present.

In the Italian approach, the relevant accidental scenarios are directly derived from the Seveso II safety reports, without the application of any standardization criterion. Thus, the accidental scenarios analyzed in the QARA study were the starting point for the application of the method. The first step was the evaluation of the four different damage areas and the attribution of the frequency class to each scenario. The results are summarized in Table 1. Fig. 6 shows the damage areas, identified by the higher land-use category allowed. The damage areas falling entirely inside the industrial areas were not reported in the figure.

The second step of the application required the assessment of land vulnerability classes: according to the land-use pattern definitions [19], the vulnerability class of each area of interest was estimated. All the residential and industrial areas inside the damage circles shown in Fig. 6 were analysed, and the results are reported in the figure.

Fig. 6 evidences that the land-use patterns of two areas resulted not compatible with the allowed development classes. The first is the area of Cotone. Here the maximum allowed vulnerability is C. However, in these areas several indicators led to classify the vulnerability as B.

The second area is represented by the port. As specified above, in this area there is a transit of more than 3.5 million persons per year, that corresponds to about 10,000 mean transits per day. Installations with more than 100 passengers/day correspond to a B land-use pattern, while in the area the maximum acceptable land use pattern is E. Therefore, the land use in these two zones is not acceptable according to the Italian land-use planning criterion, and risk reduction actions are required.

3.5. Hazard reduction actions required

From the application of the LUP methods to the Piombino area, some conclusions may be drawn about the mitigation actions that should be considered, with the only exclusion of the zone of the touristic docks. The risk-based methods indicate that the individual risk is compatible with the present land use of the area. However, the societal risk is considerable, mainly due to the situation of the port. The Dutch criterion clearly indicates the need for a reduction of the societal risk, that may be achieved by strategies as: (i) actions on risk sources, as technical measures to reduce the frequencies of the possible accidents, or the expected consequences; or (ii) actions on population, as moving the vulnerability centres away from hazardous areas.

On the other hand, the consequence-based criteria show that the consequences of the catastrophic toxic releases are not tolerable in the area. Thus, a clear indication comes from these methods for the reduction or the elimination of the pressurized ammonia storage. Hazard reduction actions proposed by the local authorities were examined in this perspective.

4. Evaluation of proposed hazard reduction actions

4.1. The hazard reduction actions proposed

Four different hazard reduction actions were proposed by local authorities:

1. The construction of a “buffer” parking zone for the touristic vehicles waiting to be loaded on ferry-boats.
2. The construction of a separated dock for the commercial traffic in a new harbour area.
3. The construction of a new road to access the port and the industrial area.
4. The elimination of the pressurized ammonia storage (risk source no. 10 in Fig. 1).

Action 1 was proposed by the port authorities, in order to clear the area of the docks from vehicles waiting for the loading procedures. This action could both increase the safety of the loading and unloading operations and reduce the number of people exposed to the hazards arising from the hazardous substances in the area.

Action 2 was included within the port development plan. New loading yards and docks should be realized north of harbour area, and will be dedicated to the industrial and commercial traffic. This should generate a physical buffer between the touristic and commercial traffic, shifting the risk sources due to the loading/unloading operations of hazardous substances away from the areas dedicated to the touristic traffic.

The new route to access the Piombino port and industrial area (action 3) should be dedicated exclusively to commercial traffic, thus avoiding that vehicles carrying hazardous substances pass through the residential areas of the town. The new route is shown in Fig. 7.

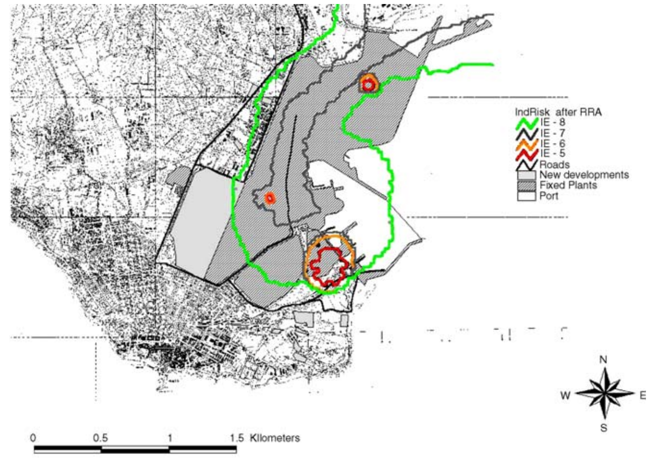

Fig. 7. Individual risk map after hazard reduction actions.

Action 4 is possible since the P2 plant uses ammonia to produce hydrogen. A new methane steam cracking plant is now under construction to eliminate the need for ammonia.

4.2. Effects of hazard reduction actions on individual and societal risk

The effects of the risk reduction actions on the individual and societal risk indexes were calculated using the Aripar-GIS software. To estimate the impact of action 1, the mean number of persons present in the vulnerability centre corresponding to the docks was reduced, and a new vulnerability centre corresponding to the new parking area was defined. The incidental frequencies due to the loading/unloading operations involving dangerous substances in the harbour area (risk sources no. 14 and 15 in Table 1) were lowered from 5×10^{-7} to 5×10^{-8} events/year, in order to account for the higher safety that should be achieved clearing the area from touristic traffic. To simulate the effect of action 2, the risk sources due to the loading/unloading operations involving hazardous substances were moved to the position of the new docks. The risk sources due to the road transport of hazardous substances were modified to assess the effects of action 3. A new risk source due to road transport of hazardous substances was defined, corresponding to the new road collecting all the traffic of dangerous substances, as shown in Fig. 7. The fixed risk sources due to ammonia (nos. 10, 11, and 12 in Table 1) were removed to simulate the effect of action 4.

The individual risk map after the four hazard reduction actions is shown in Fig. 7. The calculated societal risk curve is reported in Fig. 3. After the four hazard reduction actions the societal risk becomes very low and the individual risk in the residential areas of the town becomes completely negligible. However, the four proposed action had completely different impacts on the two risk indexes.

Action 1 had a limited effect on individual risk, but resulted in an important reduction of societal risk due to fixed risk sources

Fig. 8. Z1 protection zones identified by the application of the French LUP criterion after hazard reduction actions.

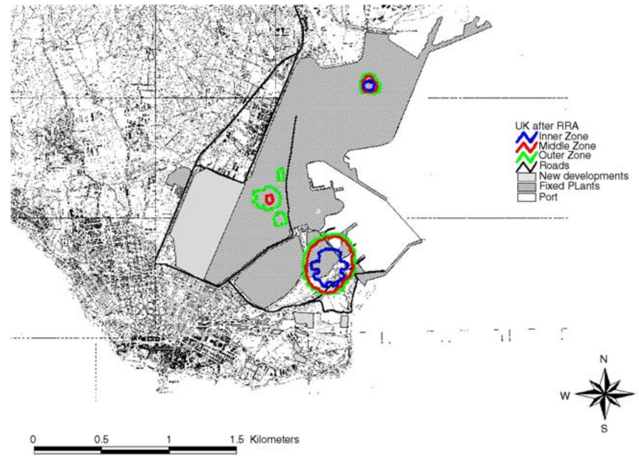

Fig. 9. Consultation zones identified by the application of the British LUP criterion after hazard reduction actions.

Fig. 10. Protection zones identified by the application of the Italian LUP criterion after hazard reduction actions.

(mainly those of the port area), as shown in Fig. 3. Action 2 resulted in a slight modification of individual risk curves, that caused the vulnerability centre constituted by the touristic docks to shift from a 10^{-6} to a 10^{-8} individual risk zone. This caused the societal risk due to the fixed risk sources of the port to become negligible, as shown in Fig. 3. Action 3 is the main cause of the important modifications of the individual risk curves that is evident comparing Figs. 2 and 7. This action confined zones with individual risk higher than 10^{-8} inside the industrial areas. After this action, also the societal risk becomes negligible, as shown in Fig. 3. On the other hand, action 4 did not result in any relevant modification of the individual and societal risk. As a matter of fact, the contribution of the ammonia scenarios to the risk indexes was negligible, since very low frequencies of ammonia releases were used in the QARA study (see Table 1) due to the high safety standards of the ammonia storage.

4.3. Application of LUP criteria to the situation after the hazard reduction actions

As shown in Fig. 8, after the four hazard reduction actions the situation of the Piombino area becomes almost acceptable with respect to the French LUP criterion. Action 4 eliminates the extended Z1 and Z2 protection zones due to ammonia releases. Only the residential area of Cotone is still within a Z1 zone.

Both the Dutch and British risk based criteria show a complete compatibility of individual and societal risk indexes in the area after the four hazard reduction actions. The 10^{-6} zone evidenced in Fig. 7 is completely within the industrial area. Fig. 9 evidences the new inner, middle and outer zones defined by the British method. Both the Dutch and British criteria should not impose, after the risk reduction actions, any limitation to LUP in the Piombino residential areas. Fig. 10 evidences the allowed land-use patterns according to the Italian criterion after the mitigation actions. As shown in the figure, the Cotone area still has a land-use pattern not acceptable, while the situation of the harbour becomes compatible.

5. Critical comparison of the LUP criteria

5.1. Comparative analysis of the present situation of the Piombino area

The first important point to remark is that, as shown above, all the four criteria applied indicated that the present situation of the area considered for the case-study is not acceptable. However, quite important differences can be found in the extension of the areas were limitations should be imposed to land use according to the different LUP criteria.

The French consequence-based method resulted the more conservative, identifying protection zones much more extended than the other criteria. As a matter of fact, not even changing the scenarios considered and adopting extremely conservative frequency values the risk-based criteria identify so wide protection zones.

The application of the Italian hybrid criterion resulted in narrower protection areas only because no standardization is imposed to the scenarios that should be considered in the analysis. The scenarios to be considered in the Italian method should be directly obtained from the safety report, and no mandatory criterion exists on which scenarios should be analyzed (e.g. the catastrophic failure of the pressurized ammonia vessels was considered "of negligible frequency" and no consequence assessment was present in the P2 plant safety report: thus, in the application of the Italian method, this scenario has to be excluded, as shown in Table 1). Results very similar to those of the French criterion would be obtained if the same scenarios were considered in the application of the two methods.

The very conservative approach of the consequence-based methods has some disadvantages, in particular when applied to existing plants and socially accepted situations as that of the case-study. Identifying too wide protection areas may have too high social costs and may cause the application of the LUP criteria to be unrealisable from a practical point of view. Moreover, since these methods are mainly sensitive to plant inventory, it is difficult to introduce criteria that take into account improvements in plant safety not affecting the inventory. The Italian method, that introduced frequency classes for each scenario, is a first step in this direction. However, the threshold values of the frequency classes of the Italian method are not optimized: no lower cut-off value is defined and a single probability class is defined for all accidental scenarios having a frequency $\leq 10^{-6}$ events/year. Thus, the French and Italian LUP methods do not directly encourage hazard reduction actions aimed to the increase of plant safety. In particular, in the Italian method, no importance is given to technical measures that reduce from 10^{-6} to 10^{-8} events/year the expected frequency of a top-event, as the mounding of a storage tank [28]. A further limitation of these LUP methods is that the hazards due to the transport of dangerous substances is not considered.

Concerning the Italian method, additional difficulties in the application of the method arise from the absence of official guidelines: it is not clear how to calculate the probability class of areas where overlapping damage circles are present. This aspect is relevant in highly industrialised areas, as the one of the case study, where many risk sources are present simultaneously and several damage circles are overlapping.

A further point to remark is the importance of the accidental scenarios to be considered in the analysis. This is one of the main factors that influence the results of consequence-based LUP methods. In particular, as discussed above, the difference in the protection zones identified by the French and the Italian method are mainly deriving from the different accidental scenarios that the two methods consider.

Coming to risk-based methods, the first point to remark is that their application is much more time-consuming and requires more complex tools than that of consequence-based methods. Moreover, if significant risk indexes should be calculated on highly industrialized areas, there is the need of an integrated QARA study. QARA studies usually result in a very accurate representation of the industrial risk, and adequate methodologies and software tools are now available [7,22,29]. However, the collection, the standardization, and the management of the data required by a QARA is still a complex task to afford.

The individual and societal risk values obtained from these methods are very sensitive indexes to represent the industrial risk, although less easy to understand for the population than the safety or damage distances obtained from consequence-based approaches. However, the risk due to the transport of hazardous substances may be quite easily taken into account in the analysis.

The application of these methods to the present situation of the Piombino area confirmed that an effective representation of industrial risk is obtained. In particular, the case-study pointed out the importance of the societal risk index evaluation to identify problems connected with the position of vulnerability centres, as the port docks, with respect to risk sources. As shown by the comparison of Figs. 2, 3 and 7, this index represents much better than the individual risk the problems of the present situation of the port area.

With respect to the results obtained for individual risk, it must be remarked that they are strongly dependent on the frequency values associated to the different accidental scenarios considered. Although even using very conservative hypothesis the results of consequence-based methods will never be obtained, the extension of the areas were land-use limitation should be imposed may be quite different, e.g. if the standard scenarios and frequency values suggested by the purple book [28] were used in the analysis. On one side, this is a positive element: the improvements in plant safety are taken into account and encouraged by these methods. On the other side, a careful analysis of the frequency values used in the analysis should be performed, and a standardization of the risk assessment procedure is required to correctly use these methods. It must be remarked that the correct assignment of frequency values is still an open problem, that is known to introduce an important uncertainty in the results.

Another important point to remark is that if the frequency values associated to the top-events of a risk source are very low, the risk indexes ignore it, independently of the severity of the possible consequences. This is the situation of the pressurized ammonia storage in the P2 plant of the case-study: no requirements come from the risk-based methods, e.g. for its mounding or for its elimination, even if the possible damage area of a catastrophic failure is very extended, as shown in Table 1.

5.2. Comparative analysis of the results of the hazard reduction actions

With respect to the effects of the hazard mitigation actions, all the LUP methods examined indicate that after the planned modification of risk sources and vulnerability centres, the situation of the Piombino area would be almost compatible with the different acceptability criteria. However, important differences were found in the effects of the different mitigation actions, and thus in the priorities that would be given to the planned modifications according to the different LUP methods.

Actions 1, 2 and 3 have a negligible effect if the French consequence-based LUP method is considered. However, action 4 (the elimination of the ammonia storage) results in a large modification of the protection zones, that causes the final situation to be almost acceptable. Thus, as expected, consequence-based criteria are extremely sensitive to inventory reductions. On the other hand, changes in the risk sources due to the transport of hazardous substances are not considered by the method, thus the effects of action 3 are not taken into account by the method. Furthermore, the very conservative protection zones generated in particular when toxic releases are considered, deriving from the severe accidental scenarios considered in the French LUP method, make ineffective realistic modifications of the position of vulnerability centres, as that planned in the harbour area (action 1).

Therefore, if the French LUP criterion should be applied, action 4 should receive the highest priority. Moreover, the results of the French method reported in Fig. 8 show that the situation of the Cotone residential area is still not compatible. Thus, the method suggests that a further hazard reduction action on the gasholder of P1 plant (risk source no. 3 in Fig. 1) might be more important than actions 1, 2 and 3.

Also with respect to the risk-based criteria the situation of the Piombino area after the mitigation actions would be compatible with respect to both the individual risk and societal risk acceptability criteria. However, the priorities of the mitigation actions are quite different. The individual risk index is mainly dependent on the expected frequencies of the accidental scenarios. Thus, the main responsible of the less extended protection zones due to hazard reduction actions, shown by the comparison of Figs. 2 and 7, is action 2 (separation of commercial and touristic docks with a decrease of accidental frequencies). Individual risk maps are also obviously dependent on the position of risk sources, thus action 3 results in an important modification of isorisk contours, although the risk values due to the transport of hazardous substances are not affected.

On the other hand, as shown in Fig. 3, the results obtained point out that societal risk is a very sensitive and accurate risk index in order to evidence the effects of mitigation actions and the risk levels for the population. Actions 1, 2 and 3 results all in important modifications of the societal risk: actions 1 and 2 cause a strong reduction of societal risk caused by accident in the port area, action 3 results in a reduction of societal risk caused by the transport of hazardous substances.

However, the results obtained also show a clear limit of the risk-based criteria. Action 4 causes a negligible effect both on societal and individual risk. This is due to the low frequencies attributed to accidents involving ammonia releases (see Table 1). Thus, a “sensitivity threshold” exists for risk-based criteria, that depends on the risk acceptability values. If frequencies of accidental scenarios are below this threshold, that is between 10^{-8} and 10^{-9} events/year for an acceptability limit of individual risk of 10^{-6} events/year, no benefit is achieved from inventory reduction or elimination of the risk source, in spite of the severity of the possible accidental consequences. This suggests that the use of risk-based LUP method strongly requires the identification of a standard set of minimum frequency values for reference accidental scenarios.

It may be concluded that risk-based criteria indicate actions 1 and 2 as prioritary. Action 3 has a strong impact if the risk due to the transport of hazardous substances is considered. On the other hand, action 4 has a negligible effect on risk indexes, and no need for mitigation actions in the Cotone area comes from these methods.

The results of the evaluation of hazard mitigation actions by the Italian hybrid criterion indicates that actions 1 and 2 have the higher impact with respect to this method. These two actions cause the class B vulnerability centre (the touristic docks of the port) to be outside the protection zones caused by the loading and unloading of dangerous substances. Also action 4 has a positive effect on the port area, although less important than that of actions 1–3. The Italian method would give a higher priority to hazard reduction actions on risk source 3 (the gas-holder of the P1 plant), that causes a critical situation in the Cotone area also identified by the French approach, than to actions 3 or 4.

6. Conclusions

The application of several European LUP criteria to a case-study showed that important differences are present in the extension of land use limitations and in the priorities of hazard reduction actions identified by the different methods. In particular, consequence-based methods seem to be more conservative than risk-oriented approaches, and to be less sensitive to mitigation actions oriented to plant safety improvement and to the protection of vulnerable centres. On the other hand, these methods are extremely sensitive to actions involving the reduction of hazardous substance inventory. Moreover, differences in the scenarios considered in the analysis resulted in extremely large differences in the protection areas identified.

Risk-based methods were found in general to be more sensitive and more suitable to evaluate the effects of risk reduction actions. In particular, the societal risk index proved to be very sensitive to the effect of risk reduction or mitigation actions. However, the results obtained confirmed that the use of acceptability criteria based on threshold values of risk indexes strongly requires the definition of a standard set of minimum allowable frequency values for the reference scenarios to obtain meaningful results, as recognized in the literature [28].

Therefore, it may be concluded that the different LUP criteria adopted in Europe showed a substantial agreement in the evaluation of the present and future situation of the case-study, even if important differences were found in the identification of effective hazard reduction actions. In this framework, a process towards the integration of some aspects of the LUP approach, as the criteria for the selection of accidental scenarios, seems to be a useful contribution to the consolidation and harmonization of LUP criteria with respect to major accident hazards.

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