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Land-use planning in the vicinity of chemical sites: Risk-informed decision making at a local community level

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Abstract

Land-use planning with respect to major accident hazards is one of the new requirements of the 'Seveso II Directive'. On top of this requirement, but also recognising the importance of the issue for the control of major accidents, the various European Member States have developed or are developing adequate procedures, approaches and criteria for the acceptability of hazards or risk. At a national level, various criteria are in use based either on 'generic distances', or on the level of consequences, or on the level of risk. At a regional and local level, however, local particularities and the presence of multiple and usually conflicting objectives — such as reduction of risk with simultaneous increase of the benefit from exploitation of land — seem to be of great importance in decision making. The paper focuses especially on the local level and it presents a methodological framework to take these conflicting objectives into account. Furthermore, it discusses the application of this methodology in an interesting case study and it demonstrates the useful insights and the substantial aid with which local planners can be provided.

Keywords: Land-use planning; Major accidents hazards; Seveso directive; Safety distances; Risk informed decision making; Multi-criteria decision making; Reference Point method

1. Introduction

The Council Directive 82/501/EEC [1], the so-called 'Seveso Directive', constituted a first stage in the harmonisation process of the legislation for the control of major

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accident hazards. Pulling from the experience gained through the application of the Directive and in the light of the accidents at Bhopal and Mexico City, which demonstrated the hazard that arises when dangerous sites and dwellings are close together, the Council called the Commission to include in the forthcoming 'Seveso II Directive' [2] provisions concerning controls on land use planning when new installations are authorised and when urban development takes place around existing installations.

The new Council Directive 96/82/EC [2], among other requirements, included provisions for land use planning. Indeed, the Directive recognises the scope and objective of land use planning which is to ensure that the likelihood and the consequences of the potential accidents are taken into consideration when decisions are made concerning siting of new installations, modifications of existing installations, and proposal for new developments in the vicinity of establishments.

In more detail, Article 12 requires the following.

- That the Member States ensure that the objectives of preventing major accidents and mitigating the consequences of such accidents *are taken into account* in their land use policy and especially through controls on the siting of new establishments, the modifications to existing ones, and new developments (residential areas, areas of public use, transport links, etc.) in the vicinity of existing establishments.
- That their land-use policy takes account of the need to establish and maintain *appropriate separation distances* between the establishments covered by the Directive and residential areas, or other areas of particular interest.
- That the land-use policy takes account of the need for *additional technical measures* in existing establishments so as not to increase the risk to people.
- And that all competent authorities and planning authorities set up appropriate *public consultation procedures* to facilitate the implementation of the land use policies mentioned above.

The Directive itself does not include any detailed prescription or suggestion on the length of the separation distances. On the contrary, it allows the Member States and the competent authorities to quantify them and to evaluate their adequacy. The competent authorities of each Member State are also responsible for setting up procedures facilitating the implementation of land-use planning policies. The political, cultural, structural, technical and other differences of the Member States are thus recognised as a parameter of distinction. In order to provide help to the competent authorities of the Member States in complying with Article 12, Guidelines [3] have been elaborated by a European Commission Technical Working Group which was set up for this purpose. The guidance document was published in February 1999, and it refers both to the use of existing technical approaches and to procedural issues.

Even with the aid of the published Guidelines, land-use planning has proved not to be an easy issue to deal with. As it has been discussed in detail in Ref. [4], many countries do not have consolidated procedures and criteria to cope with the subject. Moreover, even those countries that have well-defined procedures and criteria, and which exhibit a large expertise in dealing with safety, keep their system under continuous review. Questions like "what is the adequate separation distance?" and "how safe is safe enough?" should be addressed in the context of land-use planning. Moreover, many and complex parameters are connected to the issue, further complicating it. Considerations of socio-economic character, such as the benefit from exploitation of land, employment opportunities, importance of the establishment for the national economy, and benefits for the local community from the operation of the plant, increase the dimensionality and the complexity of the problem and prompt to a wider context for solving it than the pure technical one.

Without doubt local communities are the ones directly affected by land-use planning decisions. The local population is exposed to risk and this population will mainly gain the benefit from exploitation of land or from plant operation. Issues like employment opportunities and coping with the historical legacy of incompatible development — which is common in all European countries — are of major concern for the local community. It is therefore exactly this local population that has to decide which level of risk is acceptable and to judge the alternatives according to regional and local particularities. Of course, such a decision always has to be risk-informed. Risk-informed land-use planning decision making at a local level will be extensively discussed in the following sections.

2. Land-use planning decisions in a national and in a local context

As mentioned above, in the European environment there are countries that have already established well-structured procedures for taking major accident hazards into account in land-use planning, and countries in which such procedures are under development [3–6]. In the latter, the control of land-use planning in the vicinity of hazardous installations is covered up to now by legislation for physical planning and consists of procedures in which accident hazards are not explicitly considered in land-use policies. However, in view of the Seveso II requirements, specific and explicit new regulations are currently under development.

From the methodological point of view, the approaches followed in those countries where consolidated procedures and criteria have been established can be divided in three categories.

- The determination and use of *'generic' separation distances* depending on the type of activity rather than on a detailed analysis of the specific site. These safety distances usually derive from expert judgment and are mainly based on historical reasons, experience, rough consequence calculations or the environmental impact of the plant. Generic separation distances according to the type of activity have been established and used in Germany and Sweden and have been proposed in other countries. The use of similar tables of generic distances for screening purposes, i.e. as a checklist to ensure compatibility of land uses at an early stage of the analysis, which is in use in many countries, should be distinguished.
- The *consequence-based* approach, which focuses on the assessment of consequences of a number of conceivable scenarios (reference scenarios). Certain endpoints of the consequences are determined in terms of the levels of the physical magnitudes (concentration, thermal radiation, overpressure) that cause harm, corresponding to certain levels of the undesired effect (fatalities or irreversible effects). Decisions on

land-use policy are based on the distance to these endpoints corresponding to the worst among these reference scenarios. The method is used in France and has been proposed for many other countries.

- The *risk-based* approach, which focuses on the assessment of both consequences and probabilities of occurrence of the possible accident scenarios. The results are quantified in terms of individual risk (probability of fatality for an individual located at a certain point around the plant and continuously exposed to risk) and societal risk (probability of occurrence of any accident resulting at fatalities greater than or equal to a specific figure) and criteria have been set for both these measures. The approach is followed in the United Kingdom and the Netherlands (however, with different criteria and practical details) and has been proposed for many other countries.

For a given installation, the ‘consequence-based’ approach will show the consequence area for lethal effects and serious injuries resulting from the scenarios assessed, while the ‘risk-based’ approach will show an area within which there is a given probability of a specified level of harm resulting from the large number of possible accident scenarios. A more extensive analysis of the approaches and details on their practical implementation can be found in Refs. [3,4].

The above well-structured procedures and robust criteria have been established in the various countries at a *national level*. The criteria define the level of acceptable risk or hazard, either in terms of suggested separation distances, or in terms of acceptable consequences or risk, and set certain restrictions in the development and land-use plan if these conditions are not met. It is, however, the *local level*, where the relevant decisions are going to be made, and it is the local society that is going to confront the implications of these decisions. The criteria have been established at a national level and are only based on safety grounds. It is widely recognised that except for safety, other parameters also affect land-use planning decisions. For that reason, the character of the safety criteria is usually consultative, leaving to the local authorities the responsibility to judge other issues/parameters and make the final decisions.

The fact that risk management decisions mainly affect the local community has been recognised very early (see, for example, the American legislation with the ‘Emergency Planning and Community Right-to-Know Act’ [7]). Indeed, multiple parameters affect the land-use planning decisions, which, in addition, are often conflicting. Thus, from the safety point of view, hazardous installations should be separated from population centres and long population-free zones should ensure the population’s safety. On the contrary, from the economic point of view, land is an economic good, and keeping large areas unexploited decreases the economic profile of the region, with subsequent results to the population’s well-being. A need therefore arises for assessing an ‘adequate’ level of protection, a ‘best-compromise’ between safety and economic exploitation. Other parameters affecting land use planning decisions include employment opportunities, importance of the establishment for the local economy, benefits for the local community from the operation of the plant. All these parameters are of much more interest for the local community, which has to find a *compromise* solution. The *needs* for development and for availability of land for other uses (residential, recreation, etc.) are needs of a local character, as well. *Constraints* of various type and character are also present in a local context. Last but not least, the *involved parties* including industry, authorities, employees, the population and groups of interest bring at the stake different priorities and values to be taken into account in the decision process. There is therefore no doubt that a multicriteria decision framework would be valuable especially for an analysis of the problem in a local community context.

3. A multi-objective methodological framework for the land-use planning problem

The methodology that has been developed comes to cover exactly this need. The principles of this methodology have been presented in Refs. [8,9], whereas the applicability in the problem of emergency planning has also been validated [12]. However, consolidation, implementation and validation of the method in the land-use planning problem were performed within the LUPACS project. LUPACS (Land Use Planning And Chemical Sites) is a research project partially funded by European Commission (DG XII) in the context of the Environment and Climate Programme (area of technological risks) of the Fourth Framework Programme. The project was carried out in the period May 1996–April 1999 with the participation of four research institutions (RISØ National Laboratory (DK), National Centre for Scientific Research 'Demokritos' (GR), EC-Joint Research Centre (Ispra), and Université Paris VI Laforia (F)), two central authorities (Swedish Rescue Services Agency and Danish Emergency Management Agency) and three regional/local authorities (County Board of West Zealand (DK), Community of Fredericia (DK) and County Board of Södermanland (S)).

The proposed method, which attempts to address the problem from a multiobjective point of view, is described in detail in Refs. [10,11]. Here, only the principles will be briefly explained.

The general methodological framework is the one of multicriteria decision analysis as was set out by Keeney-Raiffa [13] and others. The main concept claimed here is that the decisions on land use planning and especially at a local community level have to be made taking as many objectives into account as possible. This way all (or as many as possible) of the important concerns of the local society can be taken into consideration and the solution expresses in a better way the whole issue. The framework for this analysis consists of five steps:

(i) Determination of alternatives;
(ii) Determination of consequences;
(iii) Determination of constraints (if any);
(iv) Preference assessment; and
(v) Determination of the 'optimum' alternative.

The first step of the procedure consists of determining all the alternative actions of the problem, amongst which the 'optimum' action is to be selected. Although the determination of alternatives is usually considered as the easiest and most 'straight-forward' part of the analysis, in real-world problems the determination of all possible actions is not an easy procedure. On the contrary, it requires special skills and a lot of imagination to identify all the alternatives of a problem. For the land use planning problem in the present methodological context, the following definition of alternatives (decision space) is adopted: Assuming that the area around the plant is divided into M regions/cells (of arbitrary shape according to the physical borders), N possible Land Development Types (LDTs) for each cell are considered. When the LDTs for all of the cells are defined, their combination constitutes a Land Use Pattern (LUP). The decision space of the problem consists of all possible LUPs, which are defined as combinations of LDTs at each cell around the plant. Examples of possible LDTs are Industrial, Residential, Residential with high population density, Recreational, etc. A LUP on the other hand may determine that one cell/region be used for Residential purposes, the second for Industrial use, the third one for Recreation, the fourth again for Residential, etc. It is clear that the total number of alternative LUPs is N^M, an extremely large number for real-world applications.

The second step consists in determining the objectives that the various alternative actions are trying to achieve and in defining measures of effectiveness in order to measure the degree of achievement of each objective. Each alternative action, if adopted, will result in a number of consequences, related to the objectives of the decision maker. These consequences constitute the evaluation criteria for the alternative actions. The *consequence* or *outcome variables* quantify the performance of each alternative with respect to the criteria, and the range of their possible variables constitutes the *consequence space*. In the land use planning problem, the consequence space consists of various categories of the anticipated adverse health effects of the potential accidents as well as of various categories of socio-economic impacts. Conflicting objectives arise when attempting to optimize simultaneously these consequences.

In principle, the decision maker(s) should express all important concerns in the form of objectives and measurable criteria. A suitable set of criteria may include the following:

- the corresponding risk profile (individual risk contours, societal risk curves),
- expected number of fatalities,
- expected number of fatalities among the sensitive population,
- expected number of injuries,
- the benefit from land development,
- various costs (e.g. for siting an installation in the specific site),
- approximation to labour sources,
- approximation to transportation routes,
- level of routine emissions, noise, and accidental environmental consequences,
- other specific aspects associated to the site selected (e.g. specific tax status).

For solving the problem, the use of the concept of efficiency was made, which — among other advantages — does not require a formal establishment of a priori value tradeoffs among the objectives. In simple words, this concept means that a LUP is efficient if there is no other LUP resulting in better consequences. The proposed methodology yields the set of efficient LUPs and the choice of the preferred alternative is confined among the alternatives of this subset of the decision space. In this way, problems deriving from the lack of acceptability and dependability of predetermined value tradeoffs are alleviated and the direct choice of a preferred LUP out of the set of efficient LUPs offers greater insight and provides a more practical framework for discussing the reasons of a particular choice. An investigation of the conditions for the case of uncertainty showed that, under mild assumptions for the form of the utility function, the methodology can be applied in the case of uncertain consequences, too.

The problem of the large number of alternative LUPs is tackled through a stepwise approach. Starting from the first cell of the study area, the method compares the possible LUPs preserving only the efficient ones. These are combined with all possible LDTs of the next cell and the corresponding consequences are added. Comparison of the total consequences reveals the new efficient LUPs and the process continues up to the last cell.

In order to facilitate the selection of a most-preferred solution among the non-dominated ones, a formal multicriteria method was adopted. It is the Reference Point method (see Refs. [14–17]), which is one of the most commonly used methods for forming an order of preferences between non-dominated alternatives. The method consists in identifying a point in the space of the representative criteria of the decision-maker's *aspirations*: this point is conventionally called *reference point*. It is an interactive and iterative method [18]. The decision-maker's choice induces a complete ordering of the alternatives in the criteria space on the basis of the concept of the *distance* from the Reference Point.

4. Description of the case and assessment of risk profile

4.1. Description

The case concerns the proximity of a chemical site with industrial and residential area, and the future plans of the company to extend its activities with production/storage of new products and of the local community with developments in the vicinity of the plant and expansion of the residential area towards an attractive resort.

The establishment, located at the bank of a river near its estuary to the open sea, produces among other chemicals sulphuric acid and oleum, thus handling sulphur dioxide and sulphur trioxide in large quantities. Parts of raw material and chemicals are imported from a river-port located in the establishment, while another part is transported by rail from a nearby railway station. Similarly, the products of the company are exported through the same routes. The surrounding area is densely populated, including schools and day care centres (see Fig. 1). The zone south of the establishment — but also the land occupied by the plants — is considered very attractive due to its close proximity to the touristic resort at the mouth of the river and near the sea. A camping area is located south of the establishment (cell 15 in Fig. 1). The presence of a

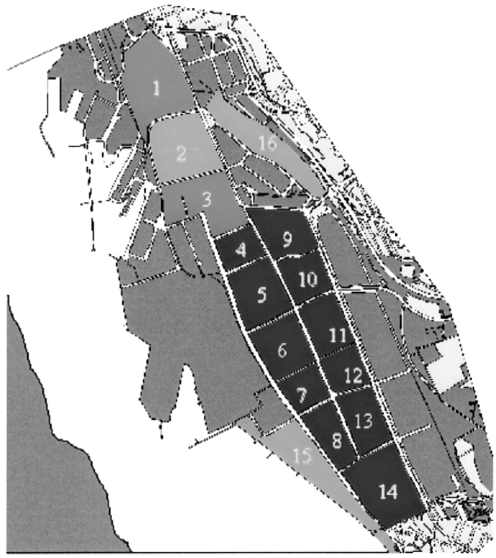

Fig. 1. The area of concern divided into cells/regions.

marshalling yard together with the railway station further complicates the problem and, as it has been discussed elsewhere [19], it increases the risk. In addition, the high value of the land makes the establishment and the surrounding zones attractive and a possible target for the city for future expansion. Future plans of the company also foresee extension of its activities with production/storage of new products. Both decisions related to the future of the company and those concerning the off-site developments (land use planning decisions resulting in expansion or reduction of population density in certain zones) make the case a very interesting application of the methodology.

The purpose of this application is to demonstrate the steps followed for the formulation of a land use planning case as a decision making problem and to discuss the benefits and difficulties from applying such a methodology in a local community context. From the methodological point of view, the following issues are of great interest and provide insights in the land-use planning problem:

- Existence of a source of risk outside the establishment (marshalling yard)
- Introduction of a multiobjective methodology and examination of multiple concerns related not only to safety but also to socioeconomic development
- Division of the area of concern into arbitrary-shaped cells, respecting the physical borders and the morphology of the area
- Use of four criteria, introducing considerations on the number of injuries and on the casualties among the sensitive population
- Application of the Reference Point method for selecting the most-preferred solution.

4.2. Risk analysis

In principle, the 'optimization' of land-use planning decisions should be based on a complete and detailed calculation of the risk profile. The individual risk of fatality at a point (x,y) around the establishment is expressed as the probability for an individual staying at the point (x,y) to die due to an accident occurred in the establishment. It is clear that many different accident scenarios can occur, each one with a different likelihood (measured by the probability of occurrence or expected frequency f_i), and resulting in a level of risk $R_i(x,y)$ at each point (x,y). The individual risk is then calculated as follows:

$$R(x,y) = \sum_i f_i R_i(x,y)$$

The frequencies of the accident scenarios can either be calculated in detail — using sophisticated techniques, such as Event Tree and Fault Tree Analysis — or estimated based on the experience from the operation of similar installations and adjusted in order to take the specific characteristics of the plant into account. Here, the second method was followed, i.e. frequencies were estimated from similar cases of the past. The consequences of the identified scenarios, i.e. the values of $R_i(x,y)$ for each scenario i, were calculated by using the Consequence Assessment code SOCRATES (Safety Optimization Criteria and Risk Assessment Tools for Emergencies and Siting) [20][1].

4.2.1. Sources of risk

The sources of risk — in terms of their location — are the following:

- Existing installation
- Expansion and new products
- Marshalling yard

In the present analysis only the risk from existing sources — existing plant and marshalling yard — was taken into consideration. Concerning the expansion of the company's activities to the production of new products it should be highlighted that such an expansion is only interesting for our point of view only if it implies the process or storage of dangerous goods. In that case, the risk profile will significantly change and the whole analysis should be repeated taking into account the new profile. Thus, from the methodological point of view not much insight is gained by repeating the calculations.

[1] For this application a certain set of tools was employed. The effect of different tools in the results of QRA has been investigated in the past (see for example the results of the first Benchmark Exercise on Major Hazards Analysis [21]). Obviously, the results in absolute terms would differ if a different code had been used. The reader may note, however, that no judgement of the level of risk is made in this approach, as it is the case in the use of risk based criteria. Here, only the ordinal value of risk is used, i.e. that alternative J has lower risk than alternative K. From this point of view, the method is less dependent on inaccuracies in the assessment code than other methods.

4.2.2. Accident scenarios

The accident scenarios considered refer to the release of sulphur dioxide from a railtank in the establishment or at the marshalling yard, during the shunting operations. Rupture of the main pipeline transferring sulphur dioxide in the establishment was also considered. The risk associated to the process plant is expected to be low.

The scenarios analysed and the relevant frequencies are described in Table 1:

It is emphasised that the frequencies depicted in the above table are not the result of any specific calculations, but are based on previous experience from similar establishments, bibliographical data, previous studies, etc., adequately adjusted to take into account the individualities and specific characteristics of the installation under study.

4.2.3. Weather data

The weather data corresponding to the actual situation were used for the calculation of risk. Wherever data were not available, a uniform distribution between known highest and lowest values of the variables under consideration was assumed. The weather data used as input variables are: wind velocity (m/s); wind direction (the actual wind rose of the area was used); stability class (A–F, according to Pasquill–Gifford classification); ambient temperature; and relative humidity.

4.2.4. Risk profile

The risk profile, as calculated by using the SOCRATES program, is depicted in Fig. 2.

4.3. Main concerns connected with the case

A number of land-use planning questions are related to the case and should be addressed by this analysis. Some questions of this kind are:

- Is the present situation acceptable?
- Shall the company expand its activity to the production of new products?
- Shall the marshalling yard continue its operation or is it better to relocate it?

Table 1
Accident scenarios

Source location	Scenario	Frequency
Railtank in the establishment	Rupture of hose during loading/unloading	5.0E − 4
Railtank in the establishment	Overpressure–Release from the relief valve	1.0E − 4
Railtank in the establishment	Puncture from another vehicle during storage	1.0E − 6
Railtank in the establishment	Valve damaged–Leakage from the valve	4.6E − 5
Railtank in the establishment	Overpressure–Relief valve blocked–Catastrophic	1.0E − 7
Pipeline in the establishment	Guillotine rupture from a vehicle crash	2.2E − 3
Railtank in the marshalling yard	Puncture from a locomotive	3.4E − 6
Railtank in the marshalling yard	Overpressure–Release from relief valve	5.0E − 5
Railtank in the marshalling yard	Overpressure–Relief valve blocked–Rupture	3.0E − 8
Railtank in the marshalling yard	Leakage from a damaged valve	4.6E − 6

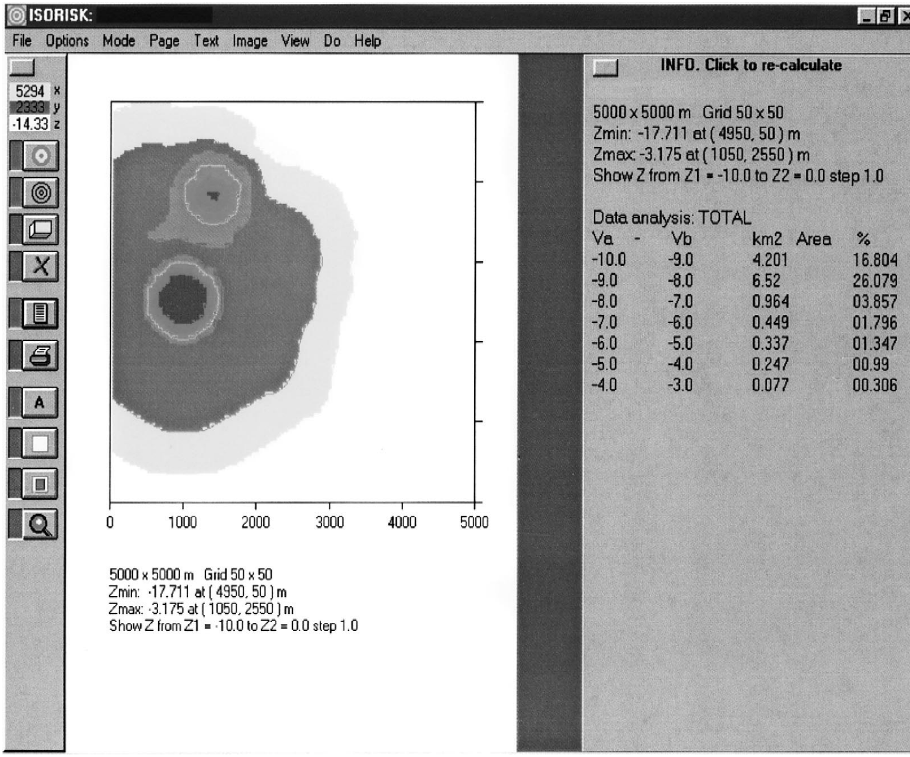

Fig. 2. The risk profile.

- Which are the ‘best’ locations for the schools? Should any of them be relocated?
- Shall the municipality expand the residential area towards the attractive touristic area?
- Shall it permit any increase in population density in the area?
- Is it better to relocate the plant to a different place?

5. Formulation of the case as a multi-objective decision making problem

According to Keeney–Raiffa [13], the main steps of the decision making process are:

(i) determination of alternatives,
(ii) determination of objectives/criteria,
(iii) evaluation of alternatives,
(iv) assessment of preferences
(v) selection of the most preferred alternative

The first step corresponds to the determination of alternative actions. Two categories of actions can be distinguished:

- actions related to residential developments, and
- actions related to the sources of risk.

In the first category the following alternative actions are included:

- Define a 'buffer' *Undeveloped* zone between the establishment and residential area
- Define an industrial zone (light industry) between the establishment and residential area
- Restrict the population in certain zones close to the establishment
- Permit an increase in population in certain zones close to the plant, either by allowing denser urbanisation or by allowing the construction of multi-storey buildings/modernisation of the housing area
- Permit the operation of schools and buildings hosting sensitive population or relocate them (it is assumed that relocation takes place to a nearby location where risk is not so high)
- Permit (or not) the operation of the camping south to the establishment
- Permit the operation of the railway station or relocate it (it is assumed that relocation takes place to a nearby location where risk is not so high).

It is worth noting that most of the above actions require a further quantification of the extent of the zones decided (e.g. extent of the 'buffer' zone, distance between the establishment and residential area, etc.).

In order to handle the definition of alternatives in a more systematic way and in order to introduce the geographical character of the problem, a more structured procedure has been adopted. The initial step of this procedure is the division of the area of concern into smaller geographical areas.

5.1. Division of the area of concern into smaller geographical areas (cells)

The main parameters of the decision (such as population density, value of land, benefit from its exploitation, individual risk, extent of consequences for specific accident scenarios) do not have a constant and unique value throughout the study area. On the contrary, they vary geographically. Moreover, individualities of certain location within the study area would be lost if it was handled as a unique area. Finally, the division into smaller geographical areas ('cells') facilitates the determination of alternatives in an easy and straightforward way.

In dividing the area into cells, certain rules of 'common sense' should be respected. For example, it is not possible to impose absolutely different uses into neighbouring pieces of land. Physical borders, such as rivers, big roads and rails, should also be used.

For these reasons the study area is divided into 16 smaller geographical regions (cells), as presented in Fig. 1.

5.2. Alternative LDTs

The determination of LDTs is based on the classification of the National Real Estate Assessment. More specifically, the following land uses are considered:

1. undeveloped
2. industrial
3. residential / small buildings (i.e. one or two dwelling buildings, low population density, commercial activities/services included)
4. residential / large buildings (i.e. apartment houses, increased population density)
5. residential (small buildings), NOT permitting buildings hosting sensitive population (such as school-children, elderly, etc.)
6. dense residential (large buildings), NOT permitting buildings hosting sensitive population (such as school-children, elderly, etc.)
7. camping area
8. railway station

LDTs 5, 6, 7 and 8 are used in order to address some of the special concerns of the problem (e.g. whether the railway station should be relocated, whether camping south of the establishment should be permitted, etc.).

5.3. Determination of alternatives

It should be stressed that not all the alternative LDTs described above are applicable for every cell. Clearly, type 6 (camping area) and type 7 (railway station) are applicable only in cells 15 and 16, respectively. Therefore, in each and every cell only one of the above Land Use Types can be applied (it is assumed that the division of the area is adequate and there is no possibility of applying more than one LDTs in one cell, e.g. both industrial and residential). The cells in which each LDT is applicable are presented in Table 2.

Table 2
Alternative land development types

Land development types	Applicable in cells
LDT 1 Undeveloped	1, 3, 4, 5, 6, 7, 8
LDT 2 Industrial	1, 3, 4, 5, 6, 7, 8
LDT 3 Residential	1–14
LDT 4 Dense Residential	1–14
LDT 5 Residential Restricted	2, 11, 12
LDT 6 Dense Residential Restricted	2, 11, 12
LDT 7 Camping area	15
LDT 8 Railway station	16

By restructuring the above Table 2, the LDTs applicable in each cell are derived (see Table 3).

An alternative LUP is determined by the combination of LDTs in all geographical cells. In other words, in order to determine an alternative LU Pattern, one has to determine the uses of land (LDT) in all geographical cells. Thus, a LU Pattern would be:

> Determine geographical areas 1, 2, 3, 4, 7, 8 and 10 as Residential areas (with low population density), area 5 as industrial, area 6 as undeveloped, areas 9, 11, 13 and 14 as dense residential (high population density), area 12 as Residential areas without sensitive population (Residential Restricted), area 15 as camping area and, finally, area 16 as the railway station.

Reference to this alternative LU Pattern (which is actually a decision) can be done by the vector of LD Types, i.e.

$$(3,3,3,3,2,1,3,3,4,3,4,5,4,4,7,8)$$

and this Pattern can schematically be presented in a map by colouring with different colours areas where different LDTs are applied.

From the above analysis it is clear that the number of alternative LU Patterns (i.e. combinations) is:

$$4 \times 4 \times 4 \times 4 \times 4 \times 4 \times 4 \times 4 \times 2 \times 2 \times 4 \times 4 \times 2 \times 2 \times 2 \times 2$$
$$= 2^6 \times 4^{10} = 67\,108\,864$$

Therefore, the number of alternatives, among which the ‘optimum’ is to be selected, is about 67 million.

Table 3
Applicability of land development types

Cells	Applicable land development types
Cell 1	Undev, Ind, Res, DenseRes
Cell 2	Res, DenseRes, ResRestr, DenseResRestr
Cell 3	Undev, Ind, Res, DenseRes
Cell 4	Undev, Ind, Res, DenseRes
Cell 5	Undev, Ind, Res, DenseRes
Cell 6	Undev, Ind, Res, DenseRes
Cell 7	Undev, Ind, Res, DenseRes
Cell 8	Undev, Ind, Res, DenseRes
Cell 9	Res, DenseRes
Cell 10	Res, DenseRes
Cell 11	Res, DenseRes, ResRestr, DenseResRestr
Cell 12	Res, DenseRes, ResRestr, DenseResRestr
Cell 13	Res, DenseRes
Cell 14	Res, DenseRes
Cell 15	Undev, Camp
Cell 16	Undev, Rail

5.4. Determination of actions related with the sources of risk

Questions related to the sources of risk are handled as separate problems, since they impose a complete change of the risk profile. Such questions include:

- the relocation of the installation,
- modifications in the process/substances used,
- expansion of the company's activities,
- relocation of the marshalling yard.

Dealing with these questions as separate problems actually means that a number of Efficient Sets is going to be produced and at a second stage these Sets will be compared with each other in order to reject the dominated solutions. This way, the set of non-dominated solutions of the overall problem will be derived.

5.5. Determination of objectives/criteria

There are two main concerns/objectives of the problem, as discussed in Section 4: (i) to increase the safety, and (ii) to achieve a high level of exploitation of land. Therefore, the criteria employed here should be safety-related and socioeconomic.

In particular, four criteria are used:

(1) Total potential loss of life (PLL). It is expressed by the total expected number of fatalities in the whole area of concern. It is calculated by the sum of the expected number of fatalities (PLL) in all 16 geographical cells. It is different for each LUP. Depends on the level of risk and the population in each cell and the objective is to minimise it. It expresses the concerns on safety of the population.

(2) Total socioeconomic benefit. It is the total socioeconomic benefit from the exploitation of the land (different for each LUP) in the whole area of concern. Expressed by the sum of the value of the land and the value of the buildings in each Land Use Type and for each cell.

(3) Total expected loss of life for sensitive population (ELLSP). It is expressed by the total expected number of sensitive population fatalities (schoolchildren) in the whole area of concern. It is calculated by the sum of the expected number of fatalities (PLL) in all 16 geographical cells. It is different for each LUP. Depends on the level of risk and the population in each cell and the objective is to minimise it. It expresses the concerns on safety of a specific population group.

(4) Total expected injuries (EI). It is expressed by the total expected number of injuries in the whole area of concern (sum over all 16 geographical cells). Depends on the level of risk and the population in each cell and the objective is to minimise it. It expresses the concerns on safety of the population. In general, risk of injury in a cell is higher than the risk of fatality.

Additional criteria may concern the reduction of oil spills in the river, the reduction of the level of noise, increase of employment, area of green space, etc. Their explicit consideration, quantification and analysis is, however, outside the scope of the present study [2].

5.6. Evaluation of alternatives

The next step of the methodology is the evaluation of alternatives, i.e. the calculation for each alternative of its 'score' in all the criteria used. The value of the safety related criteria (expected number of fatalities, fatalities of sensitive population and injuries) depend on the level of risk and the distribution of population in the area, which is a function of the LDTs. Different LDTs applied in the same cell result in different population levels for this cell (e.g. Dense Residential implies a higher population density than Residential). Similarly, the socioeconomic benefit from the exploitation of land will be different for different LDTs. This benefit can be approximated by the value of land and the value of the buildings present in each cell. Population data and data on the type of buildings and value of land for the present situation were taken from the National Real Estate Assessment. For the various LDTs, these values were extrapolated as follows:

- Undeveloped: No population–No benefit
- Residential: Basis (usually the present situation)
- Dense Residential: Increased population–Increased benefit
- Industrial: Reduced population–Reduced benefit
- Residential Restricted: As Residential but:
  - Remove schools to the closest low-risk region, i.e. from region 2 → 1 from region 11 → 14 from region 12 → 14
  - Reduce benefit by the Cost of Relocation
- Camping/Railway Station: Permit Operation (otherwise Undeveloped)

Especially concerning the safety-related criteria, their evaluation is based on the following calculations.

(a) Potential loss of life: The average risk in the region/cell is multiplied by the population corresponding to the LDT under consideration.

(b) Risk of injury: Unavoidably, the use of a non-fatal criterion introduces additional uncertainties in the procedure. However, the concern of the public to the risk of injury has to be addressed, even under these conditions. There are not many bibliographical

[2] In this application, the concern of the local community was restricted to safety issues (including injury risk) and to the proper exploitation of land. The methodology could, however, very well have been applied using environmental criteria, such as the level of routine emissions, or the level of noise, etc. The *risk to the environment* from accidental releases would also be an interesting criterion over which the various alternatives could be evaluated, although the availability of codes and tools for a quantitative assessment of these risks is still limited.

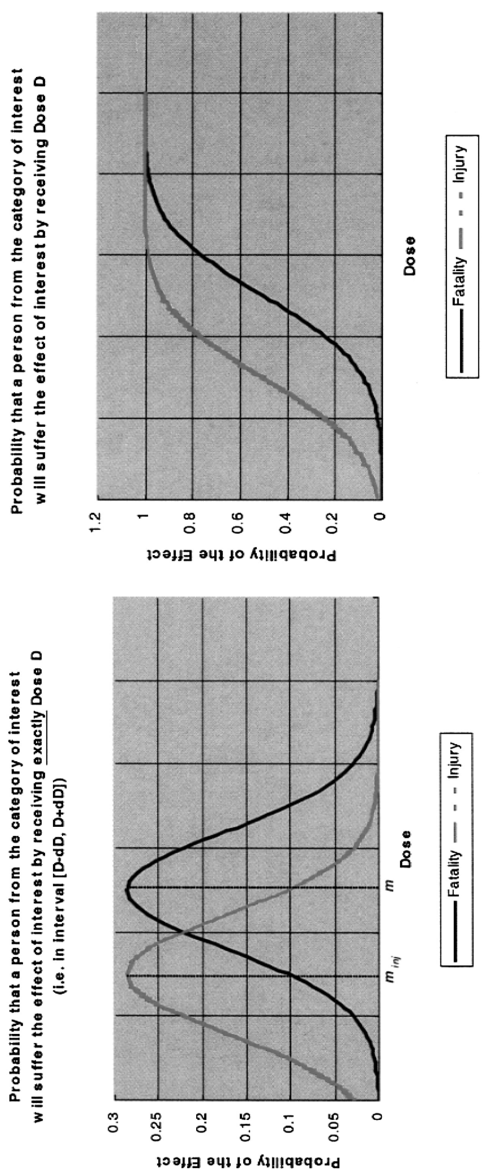

Fig. 3. Risk of injury.

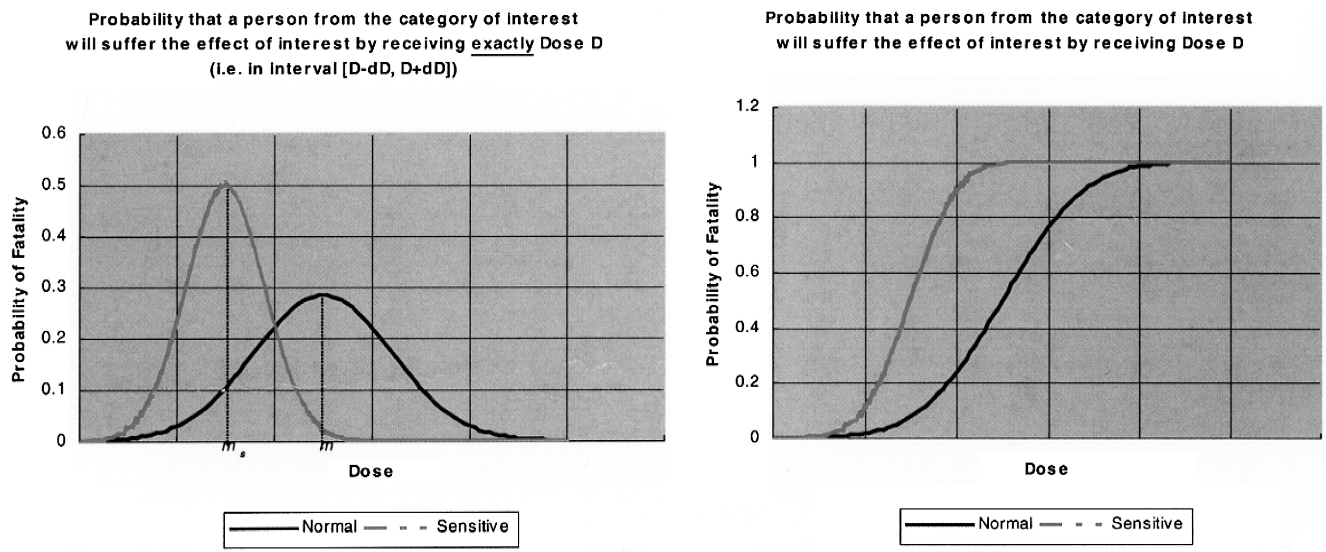

Fig. 4. Risk to sensitive population.

sources for the risk of injury, especially concerning toxic substances. Usually, it is estimated as a multiple of the risk of fatality, thus the expected number of injuries would be a multiple of PLL (e.g. $5*\mathrm{PLL}$). This consideration, which is based on the observation from past accidents that the number of injuries is much higher than the number of fatalities, does not take into account the fact that the two distributions are combined: in order for a person to be injured, (s)he first has to be alive. A different approach is proposed here. First, injury considerations are applied only to the population that remains alive after the accident. Then, as depicted in Fig. 3, for the same level of dose, the probability of injury is higher than the probability of fatality. In other words, the mean value of injury dose (dose corresponding to a pre-defined level of injury) is lower than the mean value of fatality dose.

In the calculation of fatality risk the Probit (probability unit) function is used, as follows:

$$\mathrm{Probit} = (5 - m/\sigma) + (1/\sigma)\log_n(\mathrm{Dose}) = A + B\log_n(\mathrm{Dose})$$

Therefore, a decrease of m can be expressed by an increase of the constant A. In other words, a possible way for approximating the risk of injury is to use the fatality Probit function with an increased constant A.

Moreover, for each accident scenario and each weather conditions:

$$P_{\mathrm{inj}} = P(\mathrm{inj} \mid \mathrm{alive})\,P(\mathrm{alive}) = P(\mathrm{inj} \mid \mathrm{alive})(1 - P_{\mathrm{fatal}}) = P(\mathrm{inj} \mid \mathrm{alive})(1 - R)$$

where the probability $P(\mathrm{inj}|\mathrm{alive})$ can be approximated by using an increased A in the Probit equation.

(c) Risk to sensitive population: Again the bibliography for the risk to sensitive population is poor. The approach proposed here is based on the consideration/assumption that the mean value of dose fatal to sensitive population is lower than the mean value of dose fatal to normal population, and also that the standard deviation σ of the distribution for sensitive population is lower than the standard deviation for normal population, as presented in Fig. 4. Applying again the Probit function

$$\mathrm{Probit} = (5 - m/\sigma) + (1/\sigma)\log_n(\mathrm{Dose}) = A + B\log_n(\mathrm{Dose})$$

we conclude that by adjusting constants A and B, suitable Probit functions can be generated for the estimation of risk to sensitive population.

6. Application of the methodology and main results

6.1. Generation of the efficient frontier

In problems with limited number of alternatives, a straightforward approach can be applied, consisting of the calculation of the impact of each alternative to all criteria, comparison of the results and elimination of the dominated solutions, and application of the Decision Maker's preference structure to these solutions in order to select the most-preferred one. Application of such a straightforward approach in this particular problem would require the calculation of the impact of each one from all possible LUPs (i.e. all possible combinations of LDTs for the 16 regions/cells, whose number exceeds 67 million) to the four criteria described above. Obviously this task has practical constraints.

In order to tackle this problem, an algorithm [7] was used, which determines the set of non-dominated (or efficient) LUPs. A LUP is efficient or non-dominated if there is no other LUP which is better in all four criteria (i.e. results in lower PLL value, higher benefit, less fatalities of sensitive population and less injuries). The whole setup of the problem was in accordance with the LUPACS methodology and the runs were performed using the Land Use Planning Decision Support Tool developed by NCSR 'Demokritos' to demonstrate this methodology [22]. For the share of clarity, two different runs were performed: a first one employing only two criteria, namely, PLL and socioeconomic benefit, and a second run using all four criteria. It must be emphasised that the run with two criteria refers to a hypothetical problem, where the local community is only concerned with minimising the expected fatalities and maximising the socioeconomic benefit. It is included here only in order to increase the readability of the paper and to assist the reader who is not familiar with multicriteria methodologies in following the method. Any extrapolation, however, of the results and conclusions of the following section to the four-criteria case is not valid, since the two-criteria run refers to a different (hypothetical) problem.

6.1.1. Two criteria

The application of the methodology using only two criteria resulted in 42 solutions (LUPs) presented in Fig. 5. An example of the map of the area with the proposed LDTs for each region/cell is presented in Fig. 6.

As expected, the alternative of removal of schools (Residential Restricted) does not appear in the efficient frontier in this application. The reason is that the relevant LDTs are only better in terms of sensitive casualties, which are not taken into account in the present run. Since these development types imply a cost of schools relocation — thus, reduced socioeconomic benefit — they are dominated by the relevant (non-Restricted) development types.

In principle, assessment of the Decision Maker's preferences is required in order to select the 'optimum' or 'most preferred' solution. However, an examination of the form of the efficient frontier leads to interesting conclusions. Starting from the greatest benefit and the highest number of fatalities, one finds that the fatalities can be reduced by decreasing the benefit from the exploitation of land. At a certain point, however, there is a great reduction of fatalities without significant reduction of benefit. Therefore, it might be appropriate for a reasonable Decision Maker to select the point (5.5×10^{-6} fatalities, 260 MEur) from the previous ones. Similarly, there is a region of the chart where reduction of the benefit does not result in further reduction of fatalities. This 'ceiling' value for the fatalities is 4×10^{-6}. It is a reasonable assumption that the Decision Maker will select a point with fatalities between 4.2×10^{-6} and 5.5×10^{-6} and benefit

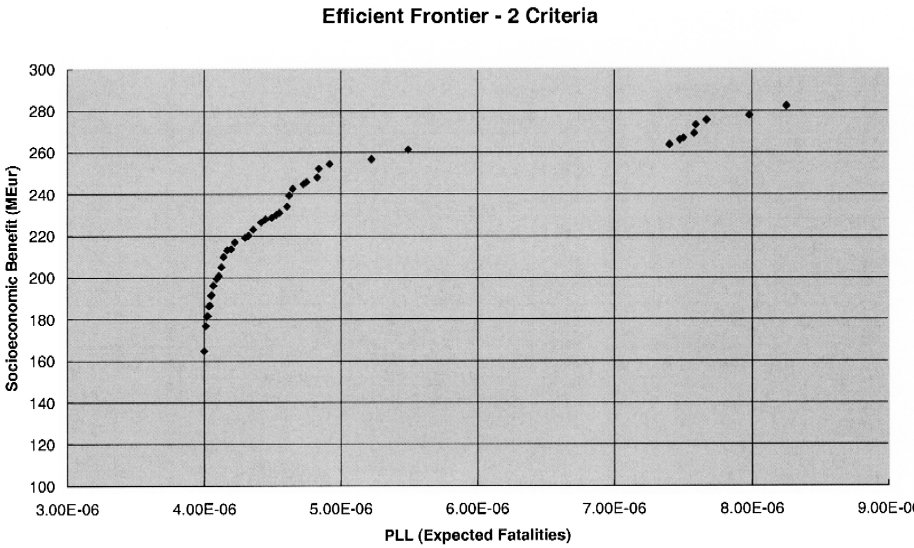

Fig. 5. Efficient frontier — 2 criteria.

ranging from 220 and 260 MEur. These simple considerations provide interesting and useful conclusions on the pattern of land use.

The complete set of efficient solutions is presented in Table 4. Both the 'scoring' of each alternative in the criteria selected and the relevant LUP are presented in this table. Therefore, for example, the policy of alternative #1 reads:

> Keep cells 4 and 5 *Undeveloped* (close to source), cells 9 and 10 *Residential*, cell 1 *Undeveloped* (due to the marshalling yard) and *do not permit* Railway station in cell 16 (due to the marshalling yard). Gain some benefit by setting *Dense Residential* to all other cells.

Alternative #2 is slightly different by permitting *Dense Residential* for cell 10 and therefore increasing the benefit with a small increase of the expected fatalities. It is clear that the Decision Maker can (or has to) assess whether he/she prefers this small increase in the benefit, 'paying' at the same time a small increase in fatalities.

Although for the selection of the most-preferred solution, assessment of the Decision Maker's preferences is required, useful conclusions can be drawn already from this phase of the analysis. Indeed, the conclusions drawn at this phase are stronger (or 'universal'), since no preferences and subjective considerations have been taken yet into account. The following conclusions can be drawn.

- The points with the highest consequences — highest benefit (*Dense Residential* everywhere — alt #42) and with lowest consequences — lowest benefit (low development as much as possible — alt #1) are included in the Efficient Frontier.
- Extremely extensive *Undeveloped* zones are not included in the Efficient Frontier. The lowest consequences (most risk-averse point) are achieved by keeping the cells

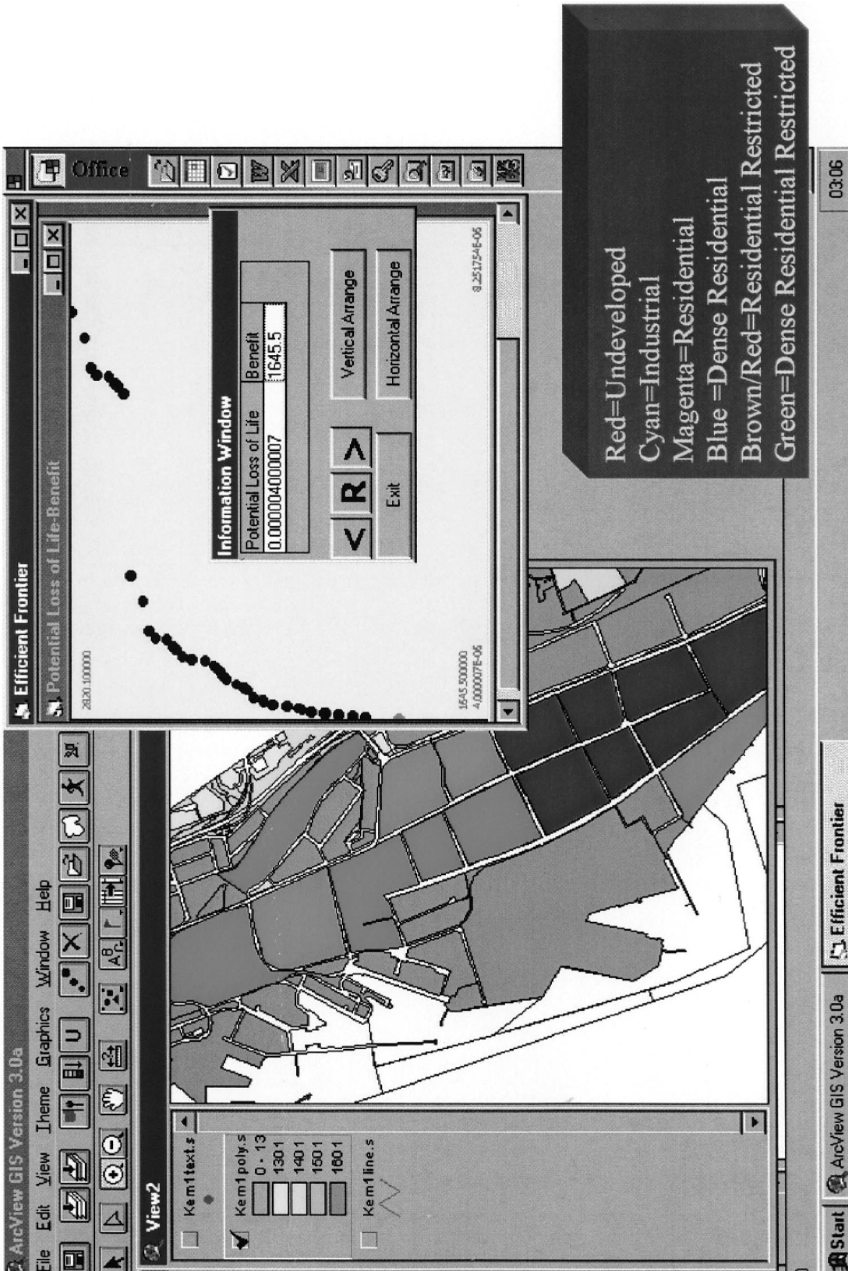

Fig. 6. Efficient frontier — 2 criteria: example of land use pattern.

Table 4
Efficient land use patterns — 2 criteria

Alternative	PLL	Benefit	Cells															
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	4.00E−06	1.65E+02	U	R	U	U	U	D	D	D	R	R	D	D	D	D	Y	N
2	4.01E−06	1.77E+02	U	R	U	U	U	D	D	D	R	D	D	D	D	D	Y	N
3	4.02E−06	1.81E+02	U	R	U	U	I	D	D	D	R	D	D	D	D	D	Y	N
4	4.02E−06	1.82E+02	U	R	U	U	U	D	D	D	R	D	D	D	D	D	Y	Y
5	4.03E−06	1.86E+02	U	R	U	U	I	D	D	D	R	D	D	D	D	D	Y	Y
6	4.04E−06	1.87E+02	U	R	U	U	U	D	D	D	D	D	D	D	D	D	Y	N
7	4.05E−06	1.91E+02	U	R	U	U	I	D	D	D	D	D	D	D	D	D	Y	N
8	4.05E−06	1.92E+02	U	R	U	U	U	D	D	D	D	D	D	D	D	D	Y	Y
9	4.06E−06	1.96E+02	U	R	U	U	I	D	D	D	D	D	D	D	D	D	Y	Y
10	4.09E−06	1.99E+02	U	R	U	I	I	D	D	D	D	D	D	D	D	D	Y	Y
11	4.10E−06	2.01E+02	U	R	U	U	R	D	D	D	D	D	D	D	D	D	Y	Y
12	4.12E−06	2.05E+02	U	R	U	U	D	D	D	D	D	D	D	D	D	D	Y	N
13	4.14E−06	2.10E+02	U	R	U	U	D	D	D	D	D	D	D	D	D	D	Y	Y
14	4.16E−06	2.13E+02	U	R	U	I	D	D	D	D	D	D	D	D	D	D	Y	Y
15	4.19E−06	2.14E+02	I	R	U	U	D	D	D	D	D	D	D	D	D	D	Y	Y
16	4.22E−06	2.17E+02	I	R	U	I	D	D	D	D	D	D	D	D	D	D	Y	Y
17	4.30E−06	2.19E+02	I	R	I	I	D	D	D	D	D	D	D	D	D	D	Y	Y
18	4.32E−06	2.20E+02	I	R	U	R	D	D	D	D	D	D	D	D	D	D	Y	Y
19	4.36E−06	2.23E+02	U	R	U	D	D	D	D	D	D	D	D	D	D	D	Y	Y
20	4.41E−06	2.26E+02	I	R	U	D	D	D	D	D	D	D	D	D	D	D	Y	Y
21	4.45E−06	2.28E+02	R	R	U	I	D	D	D	D	D	D	D	D	D	D	Y	Y
22	4.49E−06	2.29E+02	I	R	I	D	D	D	D	D	D	D	D	D	D	D	Y	Y
23	4.52E−06	2.30E+02	R	R	I	I	D	D	D	D	D	D	D	D	D	D	Y	Y
24	4.55E−06	2.31E+02	R	R	U	R	D	D	D	D	D	D	D	D	D	D	Y	Y
25	4.60E−06	2.34E+02	D	R	U	U	D	D	D	D	D	D	D	D	D	D	Y	N
26	4.62E−06	2.39E+02	D	R	U	U	D	D	D	D	D	D	D	D	D	D	Y	Y
27	4.65E−06	2.42E+02	D	R	U	I	D	D	D	D	D	D	D	D	D	D	Y	Y
28	4.72E−06	2.45E+02	D	R	I	I	D	D	D	D	D	D	D	D	D	D	Y	Y
29	4.75E−06	2.46E+02	D	R	U	R	D	D	D	D	D	D	D	D	D	D	Y	Y
30	4.83E−06	2.48E+02	D	R	I	R	D	D	D	D	D	D	D	D	D	D	Y	Y
31	4.84E−06	2.52E+02	D	R	U	D	D	D	D	D	D	D	D	D	D	D	Y	Y
32	4.92E−06	2.54E+02	D	R	I	D	D	D	D	D	D	D	D	D	D	D	Y	Y
33	5.22E−06	2.56E+02	D	R	R	D	D	D	D	D	D	D	D	D	D	D	Y	Y
34	5.50E−06	2.61E+02	D	R	D	D	D	D	D	D	D	D	D	D	D	D	Y	Y
35	7.40E−06	2.63E+02	D	D	U	I	D	D	D	D	D	D	D	D	D	D	Y	Y
36	7.48E−06	2.66E+02	D	D	I	I	D	D	D	D	D	D	D	D	D	D	Y	Y
37	7.50E−06	2.67E+02	D	D	U	R	D	D	D	D	D	D	D	D	D	D	Y	Y
38	7.58E−06	2.69E+02	D	D	I	R	D	D	D	D	D	D	D	D	D	D	Y	Y
39	7.60E−06	2.73E+02	D	D	U	D	D	D	D	D	D	D	D	D	D	D	Y	Y
40	7.67E−06	2.75E+02	D	D	I	D	D	D	D	D	D	D	D	D	D	D	Y	Y
41	7.98E−06	2.77E+02	D	D	R	D	D	D	D	D	D	D	D	D	D	D	Y	Y
42	8.25E−06	282E+02	D	D	D	D	D	D	D	D	D	D	D	D	D	D	Y	Y

Note: U = Undeveloped; I = Industrial; R = Residential; D = Dense Residential; Y = Permit; N = Don't permit (for camping/railway station).

closer to the source of risk *Undeveloped* and permitting only *Residential* use to the subsequent cells. Also, keeping the cell closer to the marshalling yard *Undeveloped* and *not permitting* the operation of the railway station is necessary (these actions lead to a serious consideration of relocating the marshalling yard). In order to gain some benefit, the remaining cells are exploited heavily (Dense Residential type of use).

- The camping area can continue its operation without problems.
- Measures for the marshalling yard/railway station are necessary if we want to reduce the expected fatalities below 4.5 persons per million years. This reduction is also possible through measures in other areas/cells; some of these should, however, remain *Undeveloped*.
- The LDT followed in cell 2 has a strong impact on the level of PLL and Benefit of the overall LU policy. Indeed, permitting *Dense Residential* in cell 2 increases the fatalities above 7.4 persons per million years (alt #35 through #42 in Table 4). Of course the impact on the Benefit is similar (above 260 MEur). For that reason, if the Decision Maker wants to keep the PLL 'low' (or 'not too high'), it is advisable to keep *Residential* use in cell 2 (not changing the present situation).

It should be reminded that the two-criteria run refers to a hypothetical problem and therefore the above conclusions — which are valid to that problem — are of no value for the 'real' problem of four criteria.

6.1.2. Four criteria

The complete application of the methodology using all four criteria resulted in 1154 solutions (LUPs) presented in Fig. 7. An example of the map of the area with the proposed LUP is presented in Fig. 8.

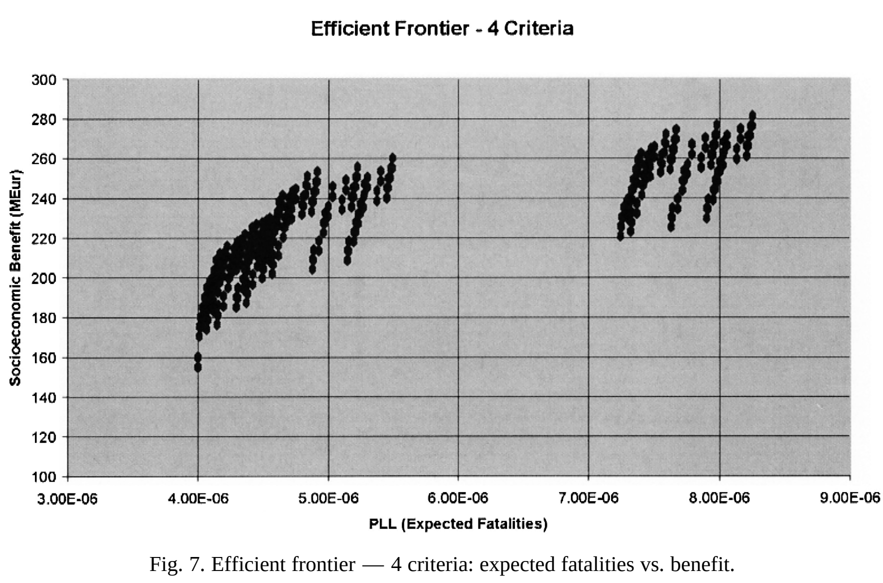

Fig. 7. Efficient frontier — 4 criteria: expected fatalities vs. benefit.

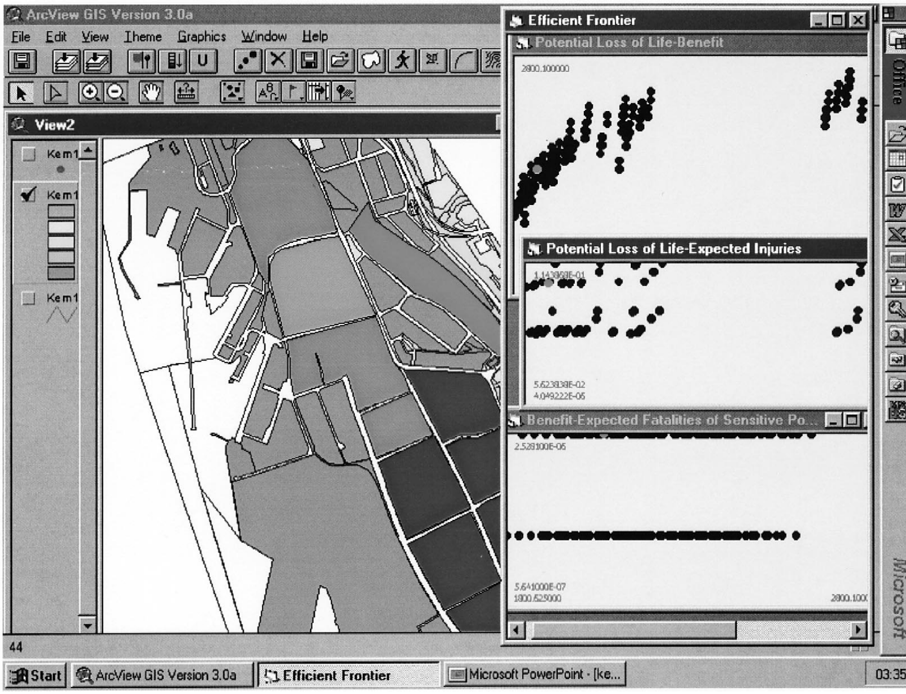

Fig. 8. Efficient frontier — 4 criteria: example of land use pattern.

In this application, where sensitivity population was taken into account, the option of school relocation appears in the efficient frontier. A pattern similar to that of the two-criteria run is depicted in Fig. 7; however, a careful analysis of the non-dominated solutions in all dimensions is required and conclusions are more difficult to be drawn.

6.2. Exploration of the efficient frontier using the Reference Point method

In the analysis performed up to this point, no assessment of the preferences of the Decision Maker took place. This assessment is necessary for the selection of the most-preferred solution. For that, the Reference Point method has been adopted and is applied here.

The Reference Point method is a Multicriteria Decision Support technique, aiming at providing aid to the Decision Maker (DM) in structuring his/her preferences and exploring the efficient frontier. It is based on the determination and use of aspiration levels. The DM is asked to express his/her aspiration levels in the consequence space and the method ranks the efficient solutions according to their distance from that point. Then, the DM is asked whether he/she is satisfied with that ranking. If not, it is possible to modify the Reference Point and get a new ranking. The procedure, which is iterative and interactive, continues until the DM selects a solution that satisfies his/her preference structure.

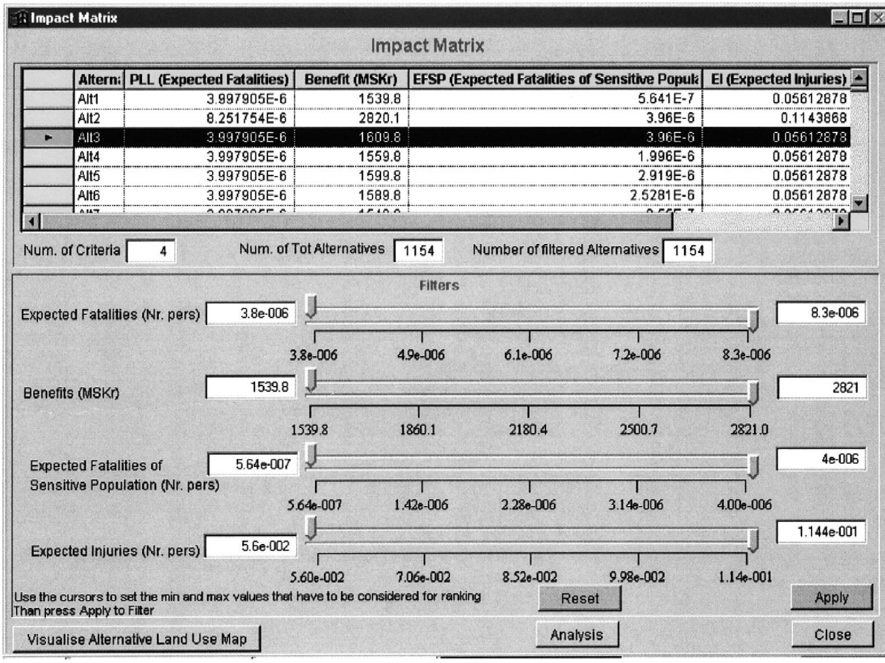

Fig. 9. Reference Point method with 4 criteria: impact matrix.

The Reference Point method has been implemented in a Decision Support Tool developed by JRC/ISIS to demonstrate this methodology. This tool was used here, and the results are discussed below, again distinguishing between two and four criteria runs, keeping always in mind that the two-criteria run refers to a hypothetical problem and is included here in order to improve the understanding of the reader to the applied methodology.

6.2.1. Two criteria

In order to get insights from the application of the methodology, various[3] Reference Points were analysed, as follows:

(i) Utopia point: Minimum PLL, Maximum Benefit
(ii) Reference point 1: A point on the diagonal, indicating that the DM is indifferent between the two criteria

[3] A formal Sensitivity Analysis, requiring a significantly higher number of runs, was outside the scope of this work, which was to investigate the applicability of the multicriteria methodology to the Land Use Planning problem. The purpose of performing different runs here was simply to investigate the implications of different Reference Points to the 'optimal' solution. However, performing a formal Sensitivity Analysis could provide with important insights and interesting conclusions could be drawn.

(iii) Reference point 2: A point on the left side of the diagonal, indicating that the DM prefers optimising PLL than Benefit.
(iv) Reference point 3: A point on the left side of the diagonal and at the lower part of the PLL-Benefit diagram, indicating that the DM strongly prefers optimising PLL than Benefit.
(v) Reference point 4: A point on the right side of the diagonal, indicating that the DM prefers optimising Benefit than PLL.

The ranking (alternative number as in Table 4) for each Reference Point is as follows.

(i) Ranking according to Utopia point ($PLL = 4 \times 10^{-6}$, Benefit = 282): Ranking Utopia: 32–31–30–29–33–28–27–26–34–25 etc.

(ii) Ranking according to Reference point 1. The point is located on the diagonal, at a distance of 15% from the Utopia point both on PLL and on Benefit. The Decision Maker is equally concerned about PLL and about Benefit. ($PLL = 4.64 \times 10^{-6}$, Benefit = 264.3): Ranking REF1: 32–31–30–33–29–28–27–34–26–25 etc.

(iii) Ranking according to Reference point 2 (low PLL, high Benefit). The point is located at the left side of the diagonal, at aspiration levels (distance from Utopia) 12% for PLL and 27% for Benefit (this means that the Decision Maker evaluates PLL as more important than Benefit). ($PLL = 4.5 \times 10^{-6}$, Benefit = 250): Ranking REF2: 29–28–27–30–31–26–32–25–24–23 etc.

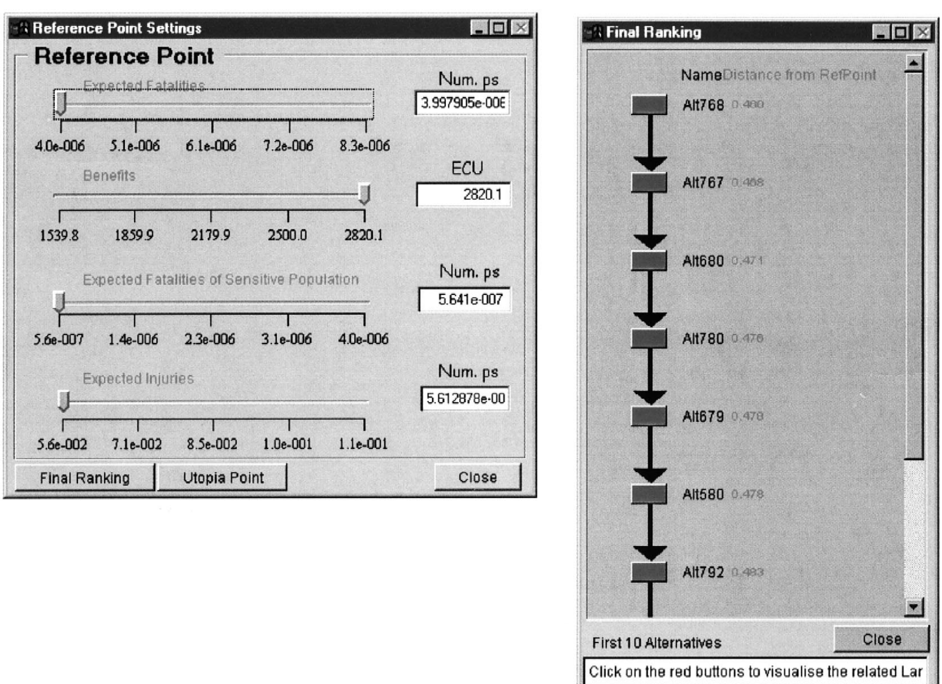

Fig. 10. Ranking according to Utopia point — 4 criteria.

(iv) Ranking according to Reference point 3 (very low PLL, low Benefit). The point is located at the left side of the diagonal and at the lower part of the PLL–Benefit diagram, at aspiration levels (distance from Utopia) 5% for PLL and 70% for Benefit (this means that the Decision Maker evaluates PLL as much more important than Benefit and this is the reason he/she can afford a 70% deviation from maximum Benefit). ($PLL = 4.2 \times 10^{-6}$, Benefit = 200): Ranking REF3: 11–10–12–9–8–7–13–14–15–6 etc.

(v) Ranking according to Reference point 4 (high PLL, high Benefit). The point is located at the right side of the diagonal, at aspiration levels (distance from Utopia) 60% for PLL and 10% for Benefit (this means that the Decision Maker considers Benefit as more important than PLL). ($PLL = 6.5 \times 10^{-6}$, Benefit = 270): Ranking REF3: 35–36–37–34–38–39–40–33–41–32 etc.

As it becomes clear from the above analysis, the most-preferred solution and the final ranking between the solutions depend on the location of the Reference Point in the

Table 5
Part of the efficient frontier — 4 criteria

Alt.	PLL	Benefit	EFSP	EI	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
6	4.0E − 6	1.5E + 2	5.6E − 7	5.6E − 2	U	***R***	U	U	U	R	D	D	R	R	***D***	***D***	D	D	Y	N
142	4.4E − 6	2.1E + 2	2.5E − 6	5.7E − 2	R	***R***	U	U	D	D	D	D	R	D	D	***D***	D	D	Y	N
146	7.3E − 6	2.3E + 2	2.0E − 6	5.6E − 2	D	D	U	U	I	D	D	D	R	D	***D***	D	D	D	Y	N
218	4.4E − 6	2.0E + 2	2.5E − 6	5.6E − 2	R	***R***	I	U	I	D	D	D	R	D	D	***D***	D	D	Y	N
226	4.5E − 6	2.1E + 2	2.5E − 6	5.7E − 2	R	***R***	I	U	D	D	D	D	R	D	D	***D***	D	D	Y	N
510	4.4E − 6	2.0E + 2	2.5E − 6	5.8E − 2	R	***R***	U	U	R	D	D	D	R	D	D	***D***	D	D	Y	Y
514	4.4E − 6	2.1E + 2	2.5E − 6	5.8E − 2	R	***R***	U	U	D	D	D	D	R	D	D	***D***	D	D	Y	Y
536	7.3E − 6	2.3E + 2	2.5E − 6	5.7E − 2	D	***D***	U	U	I	D	D	D	R	D	D	***D***	D	D	Y	Y
547	4.2E − 6	2.1E + 2	4.0E − 6	5.8E − 2	I	R	I	U	D	D	D	D	R	D	D	D	D	D	Y	Y
548	4.2E − 6	2.0E + 2	2.0E − 6	5.8E − 2	I	R	I	U	D	D	D	D	R	D	***D***	D	D	D	Y	Y
564	4.5E − 6	2.1E + 2	2.5E − 6	5.8E − 2	R	***R***	I	U	D	D	D	D	R	D	D	***D***	D	D	Y	Y
580	5.0E − 6	2.3E + 2	2.5E − 6	5.8E − 2	D	***R***	R	U	D	D	D	D	R	D	D	***D***	D	D	Y	Y
584	5.2E − 6	2.3E + 2	2.5E − 6	5.8E − 2	D	***R***	D	U	R	D	D	D	R	D	D	***D***	D	D	Y	Y
596	7.7E − 6	2.5E + 2	2.5E − 6	5.8E − 2	D	***D***	R	U	D	D	D	D	R	D	D	***D***	D	D	Y	Y
679	4.7E − 6	2.3E + 2	2.9E − 6	6.8E − 2	D	***R***	U	R	D	D	D	D	R	D	D	D	D	D	Y	Y
680	4.7E − 6	2.3E + 2	2.5E − 6	6.8E − 2	D	***R***	U	R	D	D	D	D	R	D	D	***D***	D	D	Y	Y
695	7.5E − 6	2.6E + 2	2.9E − 6	6.8E − 2	D	***D***	U	R	D	D	D	D	R	D	D	D	D	D	Y	Y
696	7.5E − 6	2.5E + 2	2.5E − 6	6.8E − 2	D	***D***	U	R	D	D	D	D	R	D	D	***D***	D	D	Y	Y
767	4.8E − 6	2.4E + 2	2.9E − 6	6.8E − 2	D	***R***	I	R	D	D	D	D	R	D	D	D	D	D	Y	Y
768	4.8E − 6	2.4E + 2	2.5E − 6	6.8E − 2	D	***R***	I	R	D	D	D	D	R	D	D	***D***	D	D	Y	Y
780	5.1E − 6	2.4E + 2	2.5E − 6	6.8E − 2	D	***R***	R	R	D	D	D	D	R	D	D	***D***	D	D	Y	Y
792	5.4E − 6	2.4E + 2	2.5E − 6	6.8E − 2	D	***R***	D	R	D	D	D	D	R	D	D	***D***	D	D	Y	Y
803	7.6E − 6	2.6E + 2	2.9E − 6	6.8E − 2	D	***D***	I	R	D	D	D	D	R	D	D	D	D	D	Y	Y
804	7.6E − 6	2.6E + 2	2.5E − 6	6.8E − 2	D	***D***	I	R	D	D	D	D	R	D	D	***D***	D	D	Y	Y
1079	8.3E − 6	2.8E + 2	4.0E − 6	1.1E − 1	D	D	D	D	D	D	D	D	D	D	D	D	D	D	Y	Y

Note: U = Undeveloped; I = Industrial; R = Residential; D = Dense Residential; ***R*** = Residential with Restrictions (Relocate school); ***D*** = Dense Residential with Restrictions (Relocate school); Y = Permit; N = Don't permit (for camping/railway station).

criteria space (which, in turn, depends on trade-off between the criteria and the aspiration levels set by the DM) and the shape of the Efficient Frontier. For example, it is expected that for ‘symmetric’ efficient frontiers, selection of any point on the diagonal as the Reference Point would result in the same ranking of the solutions.

6.2.2. Four criteria

The calculations were repeated using all four criteria (Potential Loss of Life, Socioeconomic Benefit, Expected number of Fatalities of Sensitive Population, and Expected Injuries). The procedure is presented in Figs. 9 and 10.

In Table 5, some of the solutions of the Efficient Frontier are presented. The application of the Reference Point technique resulted in the following rankings:

(i) Ranking according to Utopia point. ($PLL = 4 \times 10^{-6}$, $Benefit = 282$, $EFSP = 5.6 \times 10^{-7}$, $EI = 5.6 \times 10^{-2}$): Ranking Utopia: 768–767–680–780–679–580–792 etc.
(ii) Ranking according to Reference point 1. ($PLL = 4.5 \times 10^{-6}$, $Benefit = 250$, $EFSP = 5.6 \times 10^{-7}$, $EI = 5.6 \times 10^{-2}$): Ranking REF1: 768–680–580–780–584–767–536 etc.
(iii) Ranking according to Reference point 2. ($PLL = 6.5 \times 10^{-6}$, $Benefit = 270$, $EFSP = 5.6 \times 10^{-7}$, $EI = 5.6 \times 10^{-2}$): Ranking REF2: 696–804–548–596–695–803–547 etc.
(iv) Ranking according to Reference point 3. ($PLL = 4.2 \times 10^{-6}$, $Benefit = 200$, $EFSP = 5.6 \times 10^{-7}$, $EI = 5.6 \times 10^{-2}$): Ranking REF3: 564–510–146–514–218–142–226 etc.

7. Discussion

The method presented herein is based on the multiobjective paradigm, i.e. on the concept that the decision should be made taking into consideration as many as possible of the actual concerns of the Decision Maker(s). In addition, attempt was made to distinguish between the ‘objective’ part of the analysis (i.e. the generation of the efficient frontier) and the ‘subjective’ part, the one that is based on the preferences of the Decision Maker. This type of analysis facilitates focused and meaningful discussions between the stakeholders and helps them assess a compromise solution. If, on the contrary, a priori trade-off values were given to the objectives, the final conclusions would have been much more debatable, since the trade-off values given by one stakeholder would be different from the values given by someone else. Problems arising from the different *perception of risk*, or from amplification of risk by certain parties, could lead to divergence in an early stage of the procedure.

Some analysts have tried in the past to address safety issues using a priori the *value of life*, and trying to give it a value from the very beginning of the analysis (e.g. making trade-off between the lives saved by a proposed safety measure and the cost of this measure). First, speaking about value of human life is quite a sensitive subject and it cannot be addressed using purely technical criteria and approaches. Second, this situation is similar to the previous one. Indeed, the real advantage of using multi-criteria methods is to avoid making a priori value trade-offs between the criteria. Without doubt, each and every decision on safety issues corresponds to a value of life, i.e. to a trade-off between lives saved and funds spent. However, as it is reported in Ref. [23], the cost per life saved varies enormously between different decisions and between different Decision Makers[4]. It is therefore impossible to calculate the value of life deriving from a certain decision and use it for a different decision. Thus, even in a purely technical context, the value of life can only be used at a very late stage, after the final decision has been taken, and as a rough indication that the cost of the proposed safety measure is in line with the cost of other safety measures taken in similar cases.

Although significant effort was made by the developers of the method to make it as simple as possible and to accompany it with implementation tools, it should be recognised that its application requires a certain level of expertise. It also requires various inputs (e.g. value of land, input from Risk Assessment, etc.), as presented previously. If, however, it succeeds — as it is believed — in setting an acceptable framework that facilitates fruitful discussions, mutual understanding and the possibility for making compromises in the land-use planning issue in a way that satisfies all the parties involved, then the payback from its application is significant. Obviously, application of the method is justifiable in cases where there is conflict between the stakeholders.

8. Conclusions

At a national level, a variety of methods has been developed and is in use, helping the authorities cope with the new requirement of Seveso II Directive on land use planning, with more or less success. At a local level, however, the presence of multiple and conflicting objectives seems to be of great importance in decision making. Addressing this situation and under the general idea that land use planning is mainly an issue that has to be resolved at a local level, a methodology has been developed taking the multiple objectives into consideration and facilitating the discussions at this level.

A case study was presented, demonstrating the applicability of the methodology. The proposed approach gives the possibility to the local planners to deal with various concerns of a local character and produces meaningful results. Undoubtedly, it should not be seen as ‘panacea’ or sort of a machine producing solutions. The final decision remains always with the Decision Maker(s). What is worth noting of the method is that it facilitates discussions among different stakeholders and it gives a framework for rationalising the decisions and defending them in front of an open audience. But isn’t

[4] Indeed, as observed in a comparison of the costs of Safety and Health Regulations imposed by various federal agencies in the US ([23]), this value ranges between US$300,000 and 72 billion (values 1984) per life saved — see also the discussion on the subject in Ref. [24].

that exactly the sort of audience implied by the Seveso II Directive in its 'Information to the Public' provisions (Art. 13)?

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References

[1] Council Directive of 24 June 1982, On the major-accident hazards of certain industrial activities (82/501/EEC). Official Journal of the European Communities No L 230, 5.8.1982, as amended by Council Directives 87/216/EEC and 88/610/EEC.
[2] Council Directive of 9 December 1996, On the control of major-accident hazards involving dangerous substances (96/82/EC). Official Journal of the European Communities No L 10, 14.1.1997, pp. 13–33.
[3] M. Christou, S. Porter (Eds.), Guidance on Land Use Planning as required by Council Directive 96/82/EC (Seveso II), 1999, EUR 18695 EN, ISBN 92-828-5899-5.
[4] M. Christou, A. Amendola, M. Smeder, The control of major accident hazards: the land use planning issue, Journal of Hazardous Materials 65 (1–2) (1999) 151–178, March.
[5] S. Besi, F. Amendola, V. Belloni, M. Christou, M. Smeder, A. Amendola, U. Poli, La pianificazione dell'uso del territorio in relazione ai rischi di incidente rilevante, Convenzione ISPESL-CCR, Rapporto EUR 16412 IT (1996).
[6] A. Amendola, Approaches to risk analysis in the European Union, in: Ch. Kirchsteiger, M. Christou, G.A. Papadakis (Eds.), Risk Assessment and Management in the Context of the Seveso II Directive, Elsevier, Amsterdam, 1998.
[7] F. Fire, N. Grant, D. Hoover, SARA Title III — Intent and Implementation of Hazardous Materials Regulations, Van Nostrand-Reinhold, New York, 1990, ISBN 0-442-23803-7.
[8] H. Briassoulis, I.A. Papazoglou, Determining the uses of land in the vicinity of major hazard facilities: an optimization algorithm, in: G. Guariso, B. Page (Eds.), Computer Support for Environmental Impact Assessment, Elsevier, Amsterdam, 1994.
[9] I.A. Papazoglou, H. Briassoulis, G. Bonanos, Risk informed Decision making in land use planning, Journal of Risk Research (2000) in press.
[10] B. Rasmussen, Decision support and user needs, Contribution to LUPACS project, September 1997.
[11] LUPACS — Land Use Planning and Chemical Sites, Final Report, July 1999.
[12] I.A. Papazoglou, M. Christou, A decision support system for emergency response to nuclear accidents, Nuclear Technology 118 (2) (1997) 97–122.
[13] R. Keeney, H. Raiffa, Decision with Multiple Objectives: Preferences and Value Tradeoffs, Wiley, New York, 1976.
[14] M. Grauer, S. Kaden, A non-linear dynamic interactive decision analysis and support system (DIDASS), IIASA (1984) .
[15] A.P. Wierzbicki, A mathematical basis for satisfying decision making, Mathematical Modelling 3 (1982) 391–405.

[16] A.P. Wierzbicki, The use of reference objectives in multiobjective optimisation, in: G. Fandel, T. Gal, MCDM Theory and Application, vol. 177, pp. 468–486, Springer-Verlag, 1980.
[17] Ph. Vincke, L'aide multicritere à la decision, Editions de l'Université de Bruxelles, [Multicriteria Decision Aid] Wiley, Chichester, 1989.
[18] M. Grauer, A.P. Wierzbicki, Interactive Decision Analysis, IIASA Proceedings, Springer-Verlag, Berlin, 1984.
[19] M. Christou, Analysis and control of major accidents from the intermediate temporary storage of dangerous substances in marshalling yards and port areas, Journal of Loss Prevention in Process Industries 12 (1) (1999) 109–119, January.
[20] I.A. Papazoglou, O. Aneziris, G. Bonanos, M. Christou, SOCRATES: a computerized tool kit for the quantification of the risk from accidental releases of toxic and/or flammable substances, International Journal of Environmental Pollution 6 (4–6) (1996) 500–533.
[21] A. Amendola, S. Contini, I. Ziomas, Uncertainties in chemical risk assessment: results of a European benchmark exercise, Journal of Hazardous Materials 29 (1992) 347–363.
[22] I.A. Papazoglou, S. Karkanis, G. Bonanos, User's manual for the DSS.APR project, Contribution to LUPACS project, January 1998.
[23] J.F. Moral III, Major questions remain to be solved in updating pesticide laws, Chemical and Engineering News 65 (1987) 12–15, Sept. 14.
[24] Y.Y. Haimes, Risk Modeling, Assessment, and Management, Wiley, New York, 1998, ISBN 0-471-24005-2.