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Supporting decision makers in land use planning around chemical sites. Case study: expansion of an oil refinery

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Abstract

An approach for supporting decisions on land use around chemical sites — along with a software decision support system (DSS) — based on multi-criteria decision analysis (MCDA; and particularly on the establishment of the set of efficient solutions and letting the final selection depend on local procedures and value tradeoffs) is being illustrated through a case study where five alternative expansions of a refinery are considered along with the existing situation. Alternative land use plans are based on combinations of alternative uses of specific land cells coupled with alternative expansion options. Criteria for evaluating alternative land use plans are the potential loss of life (PLL), the noise levels and the economic benefit resulting for each specific land use plan. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Major hazard facilities pose serious threats to human health and the environment because of the possibility of accidents with severe consequences. It is desired to reduce

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the risk by reducing both the probability of an accident and its consequences, as it is imposed by the so called ‘Seveso II Directive’ approved recently by the European Parliament and the European Council [1]. This can be achieved in the following ways:

- Improve safety of the plant
- Minimize the offsite consequences
- Both

Improvement of the plant’s safety can result in both reducing the likelihood of accidents and the consequences of an accident. The latter can be achieved by limiting the intensity of the extreme phenomena (toxic clouds, fire balls, etc.) that may follow an accident. Minimization of the offsite consequences can be also achieved by controlling the uses of land in the vicinity of major hazard facilities to reduce the number of exposed individuals. Furthermore, offsite consequences may be reduced by appropriate choice of the location of the installation if such a question is being addressed for a new installation. Finally, a combination of both these approaches collectively called land use planning, may be used.

Member states in the European Union have recognized this fact and they have undertaken the obligation to develop such plans under the so called ‘Seveso II Directive’ approved recently by the European Parliament and the European Council [1]. An approach to support the establishment of such plans, has been developed through a research project named ‘‘Land Use Planning and Chemical Sites (LUPACS)’’ funded by the Commission of the European Union under contract no. ENV4-CT06-0241 (DG12-DTEE).

As the land-use-planning problem touches a number of issues (human health, environment, economic growth), it is characterized by multiple conflicting objectives and, thus, it is considered as a multi-criteria decision problem involving various stakeholders. A methodological approach drawing from the theory of multi-criteria decision analysis (MCDA) [2] and a corresponding decision support system (DSS) have been developed to support the choice of land use patterns in the vicinity of major hazard facilities. This approach is described in greater detail in Ref. [3].

Solving a land-use-planning problem requires that the latter is structured in a suitable way. The LUPACS methodology is intended to support the user in structuring the land-use situation through the identification of measures of effectiveness or degrees of achievement of the various community goals. The LUPACS methodology is also intended to support the user in developing and comparing alternative courses of action in the land-use problem. The decision making procedure includes the following steps: (a) formulation of the decision situation; (b) description of the case; (c) specification of objectives; (d) development of alternatives; (e) assessment of benefits, costs and consequences; (f) evaluation and choice; and (g) presentation and communication of the decision. More precisely, the LUPACS methodology is concerned with the land use patterns (LUPs) around a major hazard facility and is related to a number of concepts. If a number of candidate land development types (LDT) for the various parcels of land around a site are available, the problem consists in choosing the one that satisfies the goals and aspirations of the decision makers. There are several objectives potentially applicable in the land-use-planning problem and actually used, like:

- Economic
- Public health
- Environment
- Scenery
- Cultural history

''Land Use Planning'' in the presence of Major Hazard Facilities is thus set as a problem of MCDA. An MCDA problem is one in which a choice of one alternative ought to be made out of a number (small or very large) of given alternatives where each alternative is evaluated in more than one criteria. The classical approach to these kinds of problems can be distinguished in four steps [2]:

(a) Determination of consequences (which serve as decision criteria)
(b) Generation of alternatives
(c) Preference assessment
(d) Determination of ''best'' alternative

The first two steps are common in MCDA problems regardless of the specific methodology followed in the last two. The specific form of these steps in the land use planning context is next discussed.

Central to this approach, as well as to other variations, is the determination of a function that provides a quantification of the relative importance, with respect to the preferences of the decision-maker, of each and every alternative. This approach although formally appealing is not always feasible in real cases and in a policy context, where this decision is negotiated among a number of policy actors. Such cases are characterized by the following difficulties [4].

• Reasoning is defeasible, that is, further information can trigger another alternative to appear preferable than what seems best at the moment.

• The coexistence of not enough and too much information; for some parts of the problem relevant information which would be useful for making a decision may be missing. On the other hand, for other parts, the time needed for the retrieval of the existing information volume may be prohibitive for the participants to make a decision.

• Regardless of how much information is available opinions may differ about its truth, relevance, or value for deciding an issue. In addition, decision makers may have arguments supporting or against each alternative solution.

• Factual knowledge is not always sufficient for making a decision. Value judgements, depending on the role and the goals of each decision maker are often the most critical issues.

• Last but not least, decision makers are not proficient in mathematics or computer science. The system should provide them with an appropriate tool in order to participate in the discussion in a natural way. This is in accordance with the DSS pioneers vision, that is, by supporting and not replacing human judgement, the system comes in second and the users first.

An approach to decision making in these situations is presented in Ref. [5]. The LUPACS approach advertises the notion of efficient frontier, which on one hand contains all 'technical' information and on the other avoids the a priori, or explicit considerations of ‘value tradeoffs’ that can be the cause of heated debates, usually above and beyond the issues at hand.

This paper presents the application of the developed methodology in one case study, namely, the development of alternative land-use plans in a community around a chemical installation along with several alternatives regarding the expansion of the activities on the site. The paper is organized as follows.

Section 2 provides a summary of the methodology. Section 3 describes the particular problem set-up and the applications of the methodology to this case. Section 4 presents a potential use of the generated efficient frontier and the associated DSS in supporting the particular decision process. Finally, Section 5 discusses the conclusions.

2. Summary of the LUPACS methodology

As it has been mentioned in the introduction, the developed approach is based on the principles of MCDA and it can be distinguished in four steps.

2.1. Generation of alternatives

Determination of the available alternative courses of action, from which one must be chosen, constitutes the first step in the MCDA paradigm. In the land use planning context, alternative uses of land around a hazardous site constitute alternative courses of action and hence alternatives in the sense of the MCDA paradigm. On the other hand, the use of land around a site could be given and fixed and the alternative courses of action could consist in the location of a new installation or an extension of an existing installation. In both these cases, however, the changes in the sources of risk must have a geographical dimension in order to be characterized as a land-use-planning alternative. As a result, one might have either only a few alternatives to choose from or a lot. The developed methodology can handle either case but is more useful when there is a great number of alternatives to choose from.

The fundamental concept of the proposed methodology is that the area under consideration is divided into a number of smaller parts called *cells*.

Next a number of alternative LDTs are defined for each and every cell.

A LUP has been defined over the area of concern whenever the LDT for each and every cell in the area has been determined. A LUP represents an alternative course of action and the number of possible LUPs represents the number of alternatives to choose from. This latter number depends on two quantities: firstly, on the number of cells comprising the area of concern; and, secondly, on the number of alternative LDTs available for each cell.

The number of cells of an area depends on the shape and the dimensions of each cell. Any shape and dimension is acceptable by the methodology and the particularities of each cell are to be determined by the governing concerns of the land-use planners. Nevertheless, the developed methodology has considered the following types of cells.

Orthogonal cells of user defined dimensions: This was actually an approach employed in earlier attempts to develop the methodology and it has been preserved for the sake of completeness and/or as above for forming different types of cells.

Ring-shaped cells of specified dimensions: This approach is equivalent to the 'safety zoning' concept, where 'zones' around a hazardous installation are defined in terms of distances.

Iso-risk cells of any shape: Cells are defined as areas characterized by the same level of individual risk (IR) or by a level of IR within a certain range.

General cells of any type: Any type of shape and size of cells where these characteristics are determined by other land-use planning (e.g. existing LUPs), or geographical considerations.

The second element in the generation of alternatives is the LDTs available for each cell. In general, alternative LDTs may be different for each cell. A fundamental property that an alternative course of action must have in order to be meaningful in a decision analysis context is that it must differentiate itself in terms of the expected consequences from other alternatives. For this reason, the LDT ought to be defined in terms of characteristics that change the consequences that are part of the problem. For this reason, an alternative approach to the problem set up and of the methodology would be to first define the consequences against which the alternative courses of action are to be evaluated. In any event, the two stages of the methodology, i.e., generation of alternatives and consequence assessment are interrelated and interactive in nature, so that they ought to be meaningful in the context of risk informed land use planning. For example, two different building development types having different economic value but resulting in the same population density although of interest for a number of reasons (e.g. employment) are not of interest in the context of problem set-up if the set of consequences does not distinguish among various economic consequences. If only a comprehensive overall economic consequence is considered the LDT with the best performance will always be better from the other since they will be equivalent from the risk point view (owing to the same population density). Since the developed methodology was mainly focused on the risk aspects of the problem, the LDTs considered and developed were those that differentiate the risk-related consequences.

2.2. Determination of objectives and of consequences

This step of the methodology consists in the development of the set of attributes that are used to evaluate each alternative course of action. As mentioned in the previous step of alternative-generation, these two steps are in practice interactive and iterative in sequence. First, a hierarchy of objectives is developed. The hierarchy is such that elements at each level represent subobjectives serving the satisfaction of the objectives of the immediate level above. The development of the hierarchy stops when each and every objective at the lowest level of development can be quantified by a scalar quantity. Since the methodology is mainly focused on the risk aspects of the problem the set of the objectives developed has been detailed in the risk area and more general in other areas of concern. An example of the objectives and associated criteria or attributes is the following:

Objectives	Attributes
Reduce the number of fatalities in the general population (resulting from an accident)	Potential Loss of Life (PLL) (=expected number of deaths)
Reduce the number of fatalities in sensitive segments of the population (resulting from an accident)	Potential Loss of Life in sensitive segments (PLLS)
Reduce the number of injuries (resulting from an accident)	Expected number of Injuries
Reduce the level of risk at which population is exposed	Number of People exposed to a certain level of individual risk
Reduce the level of noise at which population is exposed	Number of People exposed to a certain noise level (in dBs)
Increase the overall Socio-economic well being of the population	Total Socio-economic Benefit

In order to calculate the consequences that is, the value of each attribute for each alternative course of action the following are necessary.

For health and environmental type of consequences, two types of information are necessary. First, the intensity of the potential impact from a major accident in the chemical facility(ies) in the area is necessary. For health impacts measured in terms of loss of life, this is provided by the IR profile. This profile gives for each point in the area of interest the probability that an individual of the general population will die as a result of an accident in the chemical facility. Similar profiles for risk of death for sensitive individuals or for risk of injury are necessary for the corresponding attributes. For environmental impacts, other types of profiles as concentration of a particular substance at each point of the area of interest is necessary. Such profiles are obtained from detailed quantitative risk analysis.

Second, necessary element for attribute evaluation is the population profile exposed to the various types of health risk or environmental impacts.

If the locations of the sources of hazards are given and invariable for the problem at hand then the risk profiles and the environmental impact profiles are given and fixed for each and every alternative course of action. What changes in this case with each alternative is the population profile exposed to each type of risk. If the location of the hazardous sources are varying as part of the alternative courses of action and the LUPs are fixed then the population profiles are also fixed, while the risk profile ought to be recalculated with each alternative. Finally, both risk profiles, as well as, population profiles are possible to vary with each alternative.

In the general case, the risk analysis results in a probability density function over the possible range of population at risk. In this project, only some special cases of this general case are considered, namely, cases when summary measures of the existing uncertainty are sufficient to express preference attitudes of the decision maker, as explained in the following sections.

2.3. Generation of the efficient frontier

Classical MCDA approaches, after the determination of alternatives and the evaluation of each alternative on the set of attributes, involve two final steps: (a) the assessment of preferences by the decision-maker; and (b) the choice of the most preferred alternative. This in general comprises the assessment of a value function and/or of a utility function quantifying preferences among certain and uncertain alternatives, respectively. A prescriptive procedure for assessing multi-attribute value and utility functions can be found in Ref. [2]. This approach, however, is not very practical or useful in a policy context where these decisions are negotiated among a number of policy actors. As a result the LUPACS methodology has adopted a different approach. Cornerstone of this approach is the fact that value tradeoffs among highly debated issues as, for example, economic benefits and public health consequences are not formally set. Such tradeoffs are unavoidable and are always made implicitly or explicitly when the final decision is made. The LUPACS methodology, however, aims not at making such a decision but rather at facilitating or creating a platform to facilitate the final choice by the appropriate people at the appropriate fora. In order to achieve this the LUPACS approach uses the concept of *dominance*.

An alternative I is said to dominate another II, if I is either better or equivalent in each and every attribute of evaluation and strictly better in at least one attribute. Comparisons in one dimension (one attribute) are rather easy since they do not involve value tradeoffs. So if an alternative results in 40 deaths and 10^6 monetary units (MU) of benefit, it is definitely more preferred to one that results in 50 deaths and the same economic benefit. An alternative is called *dominant* or efficient if there is no other alternative in the feasible set that dominates it. The set of all efficient alternatives constitutes the *efficient set* or the *efficient frontier*. The efficient set is usually a small subset of the original set of all possible alternatives. Determination of the efficient frontier for continuous decision variables is achieved with the help of techniques of multi-objective optimization. In the LUPACS approach, both the decision space and the consequence space are discrete. A particular mathematical algorithm is adopted that allows for the fast determination of the efficient alternatives out of the very large number of alternatives. This algorithm has been developed before and outside of the LUPACS project [8] and it is valid in the following two cases: (1) when expected values are sufficient to characterize attitudes towards uncertainty in each attribute (one-dimensional (1-D) risk neutrality); (2) when risk aversion or risk proneness in each dimension (attribute) can be characterized by an exponential function.

2.4. Direct use of the efficient frontier

The efficient set is usually a small subset of the original set of all possible alternatives. Further choice among the alternatives requires a preference assessment. In several instances, however, knowledge of the efficient frontier limits the practical alternatives to such a degree that the choice of the most preferred alternative is greatly facilitated.

The LUPACS approach advertises the ‘‘efficient frontier’’ as a very useful tool since it provides a platform that can facilitate the discussion between the various stakeholders. In particular, the proposed approach can remove from the debate a large number of ‘‘what if’’ questions since it can explore a very large number of alternative solutions and keep only those that can not be rejected on ‘‘technical’’ or ‘‘scientific’’ arguments. Perusal of the efficient frontier can then narrow the discussion to potential solutions in a specific narrow range of it where the actual choice might also include ‘‘sub-optimal’’ solutions that include other intangible considerations not included in the quantified analysis.

The approach has been applied in five case studies each demonstrating additional features of the methodology. The simplest case study is presented along with the methodology in Ref. [3]. The case study presented in this paper is characterized by cells defined on a risk basis and, in particular, by alternative locations for the sources of hazard. This results in a number of efficient frontiers, which are then combined to provide the overall efficient frontier.

Discussion on the choice of the final solution is facilitated by a DSS that enables the simultaneous perusal of the efficient frontier and the implied land-use policy by any point chosen on the frontier. Details of this DSS are given in Appendix A.

3. Problem definition of case study

3.1. Short description of the installation and of the surrounding area and background

The refinery is a ‘Seveso II Directive’ [1] plant established in the early 1960s close to a medium sized city of about 30,000 citizens in an urban area. The refinery is located close to the coast with a relatively large harbor. In 1994, the owner of the refinery submitted an application for a new process plant and storage facilities to the county and to the city council. About 300 people were employed at the refinery and about 100 new jobs would be created by the expansion. Until 1991 the refinery’s capacity was approximately three million tons crude per year. It produces oil products like gasoline, oil, light and heavy fuel, kerosene, propane and butane. After the expansion a natural gas condensate is also designed to be produced increasing the throughput capacity to five million tons per year. Including the proposed expansion the refinery occupies an area of approximately 64 ha (780 $\times$ 850 m) and it consists of: the process area (on site), the crude storage tanks (off site), additional propane and butane storage tanks and truck loading facilities and pier facilities (about 1 km from the refinery). High risk storage includes three spherical tanks with propane and butane. The proposed expansion will comprise a new process flare, a new condensate storage tank, a new LPG storage tank and some new petrol storage tanks. Totally, there are seven spherical and two cylindrical storage tanks on site. The two largest butane tanks have a capacity of approximately 2830 m^3 each at a pressure of 4 bar.

A safety analysis consistent to the ‘Seveso Directive’ was delivered to the competent authorities in 1989. According to the authorities, the safety level in the refinery was high and the plant was approved with some minor objections and recommendations. On the other hand, the company uses a number of improvement tools and methods, such as International Safety Rating System (ISRS), Life Cycle Analysis (LCA), ISO 9000 and 14000, Environmental Management and Audit Scheme (EMAS) and Synergy (accident reporting and follow-up system). A risk analysis for the proposed expansion was also performed.

The area around the refinery contains the following (distance from refinery in brackets):

- closest school (750 m)
- local roads bordering the refinery
- public ferry terminals (1.5–2 km)
- a cluster of residences with about 25 houses (500 m)
- residential area with 250 houses (1.2 km)
- a small village with 25 houses (200 m)
- a privately owned castle (750 m)
- 10 employee refinery owned residences bordering the refinery fence
- a power plant, 1467 MW (250–500 m)
- high voltage lines and pylons run across the field east of the refinery.

An application has been submitted to the county concerning the establishment of a new process plant and storage facilities. The land-use planning situation can be characterized as an expansion of an existing hazardous installation, i.e. siting of a new installation, where only minor changes of the LUPs around the site are possible.

The decision to consider the expansion was based on an Environmental Impact Assessment following EU requirements (Directive 85/337) including an assessment of the impact on environment, property and human lives during normal operation and in case of an accident.

The decision process involved different actors:

- the municipality (officials and politicians),
- the county (officials and politicians),
- the State Emergency Management Agency: approval according the mergency legislation and on the extent of safety zones,
- the Working Environment Service and the local office: advisor on safety level, safety zones, approval of safety levels,
- the company staff.

During the planning period, two public hearings were arranged with invitations to the public and non-government organizations to comment on the draft approval of the expansion. Some of the concerns phased during the examination period of whether to grant permission for the company’s expansion are listed below.

3.1.1. Safety and accidents

- *Harm to human beings:* The most severe hazard for human beings onsite and offsite the refinery was probably a boiling liquid expanding vapor explosion (BLEVE) occurring at an LPG storage tank. The consequences could be injuries and deaths (burns, blast effects, missiles).
- *Environmental impact:* Release of oil products could cause harm to vulnerable recipients such as: ground surface, ground water, wetlands, meadows, streams and coast

lines. Causes for the release could be: leakage at the refinery, ship collision, failures at the waste water treatment plant, etc.

• *Impact on property:* Explosions and fires at the refinery could cause damage to property onsite and off-site.

• *Safety zones:* In connection with the approval procedure a safety zone of 300 m around the refinery has been defined. Within this zone residential, public or industrial buildings are allowed only after prior approval by the appropriate national Emergency Management Agency.

3.1.2. Public distortion and health (normal operation)

• *Air quality:* Emissions from refinery operation could be NO_x, SO_2, soot and volatile organic compounds (VOC). As part of the permission given by the county, it was required that a recovery plant was constructed to keep the ambient concentration of benzene in the air at an acceptable level. Further, the transportation of raw materials and products would contribute to the air pollution.

• *Noise:* Boiler, compressors pumps, etc. cause noise at a relatively high level. Further, noise problems could arise due to heavy vehicle traffic.

3.1.3. Environmental impact (normal operation)

• *Air quality (regional and global):* The refinery will contribute to the emission of the so-called green house gases (e.g., CO_2) which might cause climate change. Further SO_2 and NO_x are released, which contribute to acidification.

3.1.4. Cultural heritage

• *Grave mounds, archaeological objects, castles and cultural buildings:* Protection zones around these monuments have been defined in the local and regional plans.

3.1.5. Natural heritage

• *Nature protection:* Nature protection zones concerning birds, wet lands, forests, streams, lakes and coasts have been defined.

• *Visual disturbances:* Installation, lighting, equipment, flare, etc. would have an impact on the visual aspect of the area.

3.1.6. Societal / economic aspects

• *Occupation:* The refinery expansion would create approximately 100 new jobs.

• *Public costs:* The expansion of the refinery would require an expansion of the harbor facilities, an increase of the capacity of the waste water treatment plant together with the sewage system and changes in the emergency preparedness. Further, it was considered necessary that some high voltage pylons and some wind turbines should be moved.

• *Public benefits:* Increase of industrial activity would contribute to the development of the city and the region.

3.1.7. Company aspects

• *Investments:* It was within the interests of the company to keep the investments as low as possible using existing staff and facilities to the highest degree.

• *Interests:* The company would have a good access to qualified personnel, an easy access to harbor, and a guaranteed reliability of utilities systems (power, cooling water, fresh water, etc.).

3.2. Formulation of the problem and determination of alternatives

There are two aspects of the problem determining the alternative courses of action: (a) the expansion (and, if yes, its location) of the facility; and (b) the potential uses of land in the area of concern.

3.2.1. Expansion of facility

Given the potential for a significant increase in the condensate of natural gas to be processed, the company pointed out five possible solutions for refining the condensate.

- Selling the condensate to another company directly from the terminal.
- Contracting with another company to refine the condensate.
- Refining the condensate at another refinery owned by the company in another country.
- Refining the condensate at the company’s refinery in that particular site.
- Create new capacity at one of the company’s refineries elsewhere in the same country.

These general options coupled with possible expansions formulated the following six alternatives: (1) No expansion within the country. Expansion close to the existing refinery within area A with four variants. (2) South of refinery, within the fence (option K1 in Fig. 1). (3) East of refinery (option K2 in Fig. 1). (4) West of refinery (option K3 in Fig. 1). (5) South of the refinery and south of the road (option K4 in Fig. 1). A completely different alternative is: (6) A new refinery capacity at another location within

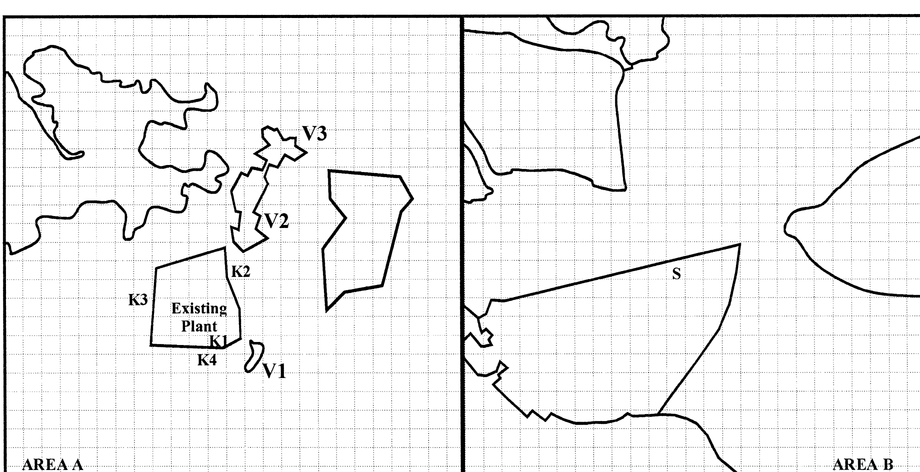

Fig. 1. General area around an existing oil refinery in area A. Possible expansions around the existing site as well as in area B.

the same country, but in a different area B (option S in Fig. 1). This position is close to a large coastal area designated for industrial activities. At this location there is a deep water harbor, facilities for waste water treatment and a large distance from the closest city.

3.2.2. Uses of land around the facility

Each of the five possible sites for the facility expansion provides the first element for alternative determination. The second element is the partition of the area in question into smaller units of land or cells, each of which will be characterized by the same development type. As area of concern, the local decision-makers have defined the area around the refinery and the area around the alternative site of the expansion. This area has been subdivided into 25×25 squares of 200 m $\times$ 200 m each (see Fig. 1). These cells have been grouped into 64 cells of general shape as explained later in this section. The next element in determining the alternatives is the assessment of the various LDTs available for each and every cell. Specific LDTs reflect the philosophy and the needs of the local or regional communities. At the time of this particular application, detailed community plans and regulations regarding allocation/position of housing and industrial areas were already in place. As a result, there was little freedom in changing existing and already approved uses of land. Risk was the new element that the local planners wanted to include into their analysis and the main objective was to test for acceptability of already established plans rather than exploring new possibilities. It was, therefore, decided that possible options would be concentrated in the form of restricting the population density in the direct vicinity of the plant, as well as, the possible relocation of a nearby village. These considerations have been formulated in the following five LDTs.

(a) *Restricted land:* Minimized human activities; protect wild life and vegetation.
(b) *Agricultural use:* Only agricultural activity is allowed in the area.
(c) *Industrial use:* Industrial and/or heavy commercial use.
(d) *Residential use:* Residential buildings and other associated activities.
(e) *No changes possible:* It is not possible or under consideration to change the existing land use.

Given these five LDTs, four general categories of cells have been distinguished.

(i) *No change possible:* All area for which no alternative land use is possible is included in this category and forms one cell regardless of the present use and/or risk level. Square lots occupied by sea or by the chemical installation itself belong to this generalized cell. All lots in this category are characterized by an LDT of type (e) above.

(ii) *Presently agricultural use:* Land presently used for agricultural purposes. This land would either retain its present use or change to restricted. Its LDT is presently of type (b) and it can only change to (a).

(iii) *Presently industrial use:* Land presently used for industrial and/or commercial purposes. Square lots in this category can retain their present use of land or change into agricultural or restricted use. Square lots in this category are of type (c) and can change to either (b) or (a).

(iv) *Presently residential use:* Land presently used for residential purposes. The use of land in this area can change into industrial, agricultural or restricted. Square lots in this category are of type (d) and can change to (c), (b), or (a).

The square lots in each of the three categories (ii) to (iv) were further divided into groups characterized by roughly the same level of IR. Twenty-one such levels have been considered (1st: 10^{-5}–5×10^{-6}, 2nd: 5×10^{-6}–10^{-6}, ..., 20th: 5×10^{-14}–10^{-15}, 21st: $<10^{-15}$). As a result, the 1250 square lots of the area around the two sites (see Fig. 1) have been merged into 64 cells: one resulting from lots of category (i) and 21 from each of the remaining three categories. It is noteworthy that this cell formation is also based on the requirement that lots characterized by the same level of risk but belonging into different geographical areas (A or B in Fig. 1) will be characterized by the same LDT.

As a result, for each alternative site for the expansion there are $2^{21}\times3^{21}\times4^{21}$ alternative LUPs.

3.3. Determination of objectives and calculation of consequences

Of paramount importance to the developed methodology is the determination of the set of attributes that can quantify the degree of satisfaction of each of the determined objectives. These were determined on the basis of the general concerns of the decision-makers presented in Section 3.1 above and the following considerations.

(1) Only objectives (attributes) that could be affected by the considered alternatives would be retained.

(2) Risk from major hazards and the role of land use planning in managing these risks was the scope of the methodology and as a result these aspects of the problem were emphasized.

(3) Alternative LUPs imply alternative population distributions around the plant site. As a result, all consequences that depend on the population distribution ought to be considered. Such consequences include public health effects resulting both from normal operation, as well as, accidents in the installation.

(4) Environmental impact has not been considered since these impacts did not differentiate substantially by each of the six potential expansion sites. Furthermore, alternative LUPs do not result in different environmental impacts from a major accident in the facility. Environmental impacts different from one LUP to the other can occur only if the uses of land themselves threaten environmentally protectable areas. Such cases have not been identified in the particular application. In addition, waste and other environmental impacts could differ between different LUPs but they were considered outside the scope of the study since they are not risk related.

(5) Offsite impact on property could be different for different LUPs but the range of possible offsite property damage from explosions and fires would not extent to distances meaningful for the scale of the present application.

(6) *Cultural and natural heritage:* Protection of cultural and/or natural elements has been taken into consideration by restricting the available LDT, for square lots containing elements pertaining to cultural and/or natural heritage.

(7) *Societal and economic aspects:* The aspects that can be affected by alternative LUPs have been taken into consideration.

All these concerns of the planners have been reduced into three general objectives:
(i) Minimize the PLL
(ii) Maximize the economic benefit

(iii) Minimize the number of people exposed to a particular level of noise

Details concerning the transition from the general concerns into the above specific indicators as well as calculation of the criteria values can be found in Ref. [3].

3.3.1. Potential loss of life (PLL)

All the effects on public health stemming from potential accidents in the facility have been aggregated into one attribute namely the number of expected deaths in the general population from an accident that can happen anytime during the lifetime of the plant.

In general, additional harm indices (e.g. cancers) and differentiation among population segments might be considered important in capturing the full extent of the impact. The proposed methodology is not limited by the number of attributes considered although there is a limit on the number of separate attributes decision makers can handle meaningfully.

PLL has been calculated through the following process. First, an IR profile over the area under consideration has been generated for each of the five possible locations of the expansion, as well as, for the case of no-expansion of the installation. Next, the population implied for each of the cells has been combined with the IR level of the cell to provide the PLL over the lifetime of the plant. The risk profile has been generated through a detailed QRA carried out for the refinery. The following 10 accident scenarios have been considered:

Scenario 1: HCl release from Power plant

Scenario 2: Hydrocarbon release from new process installations with fire ball formation

Scenario 3: H_2S release from new process installation

Scenario 4: BLEVE from LPG tanks

Scenario 5: Flash fire from LPG tanks

Scenario 6: BLEVE from LPG tank car (‘‘old’’ facility)

Scenario 7: BLEVE from LPG rail tanker (‘‘old’’ facility)

Scenario 8: Fire in crude oil tanks

Scenario 9: Fire in condensate tanks

Scenario 10: Fire in petrol tanks

Synthesis of the IR induced by these scenarios resulted in the overall risk profile [6,7] implied by the hazardous facility (refinery and potential expansion). The PLL for each LUP is then calculated on the basis of this risk profile and the population distribution implied by the specific LUP.

3.3.2. Economic benefit

Economic benefits of a LUP combined with a particular plant expansion alternative have been determined on a capital gain basis (net present value) including:

(a) value of land, mainly based on market value of houses and industrial lots;

(b) capitalized gain of employment (roughly estimated to be 1000 MU over a period of 50 years, based on 100 extra employees earning 0.2 MU a year each);

(c) Extra company-invested cost for certain alternatives (e.g. acquisition of land or extra cleaning facilities).

As a result, each LDT implies an economic benefit (when applied in a square lot) as given in Table 1. Of particular interest is the ‘economic benefit’ given for LDT4, which

Table 1
LDTs and associated economic benefits and population density

Land development types — associated parameters			
Land development type		Economic benefit	Population density
LDT1	Protected	0.5 MU/square lot	0.5 people/square lot
LDT2	Agricultural	1.0 MU/square lot	1.2 people/square lot
LDT3	Industrial	10 MU/square lot	30 people/square lot
LDT4	Residential	26.64 MU/square lot	40 people/square lot
LDT5	No changes possible		

includes the compensation cost assumed equal to the present market value of the residential area (13.32 MU/square lot). Thus, if a residential square lot was transformed to an industrial lot the drop in value or benefit would be (13.32–10 = 3.32 MU). If, however, compensation equal to market value had to be given to the owners of the square lot then, the drop in value would be equal to (3.32 + 13.32) MU. This was included in the analysis increasing the 'value' of a square lot presently characterized by a residential LDT, from the market value of 13.32 to 26.64 MU.

3.3.3. Number of people exposed to a particular noise level

Noise from the normal operation of the facility was one of the detrimental aspects of normal operation that the public around the site seemed particularly concerned of. This effect has been chosen as a proxy attribute of all health and well being effects of normal operation. In particular, the number of people exposed to a noise-level above a particular limit has been chosen as the attribute that encapsulates the detrimental effects of normal operation. The less this number the more preferred the solution is. Again only one attribute has been used in order to facilitate the demonstration of the methodology.

Given a particular expansion location for the installation a noise-level profile is established and the cells (or parts of) characterized by a noise level higher than the chosen limit are determined. Then for each LUP and for the corresponding population density the number of affected people is determined.

3.4. Generation of the efficient frontier with two attributes

As already mentioned in Section 3.2, the particular problem setup implies a very large number of alternatives LUPs. Straightforward determination of the efficient frontier is consequently prohibitive.

An algorithm that generates the efficient set without necessitating generation of all possible alternatives has been imbedded in a computerized DSS, developing the set of efficient solutions in the consequence space along with the corresponding LUPs. This algorithm takes advantage of the fact that the total consequence of a given LUP is the sum of the consequences implied by the constituent cells and the corresponding LDTs, as well as, of some additivity properties of the preference structure over the attributes [8,9].

4. Discussion of results

4.1. Perusal of the efficient frontier with two attributes

First, the potential use of the efficient frontier with two attributes is demonstrated. Each potential expansion alternative is associated with an efficient frontier representing the available LUPs in the general area of the installation. For example, the efficient frontier for expansion alternative K2 is given in Fig. 2. Following the constraints set forth by the planning team only solutions implying reduction of population have been considered. Point A in the efficient frontier represents the existing situation and corresponds to the solution with maximum benefit and maximum PLL. The LUP corresponding to point A is shown in Fig. 3a. An alternative LUP is the one corresponding to point F of the efficient frontier and shown in Fig. 3b. Moving from A to F means creating a zone north and east of the existing plant where restricted use of land is foreseen instead of the heavy industrial use along with relocation of village V1 and half of village V2. Intermediate points represent other possibilities, as point C where only the relocation described before is effected, and point E which is similar to F but without the relocation. Further restrictions in the uses of land lead to point G corresponding to the solution with absolute minimum PLL and economic benefit (Fig. 2). The efficient

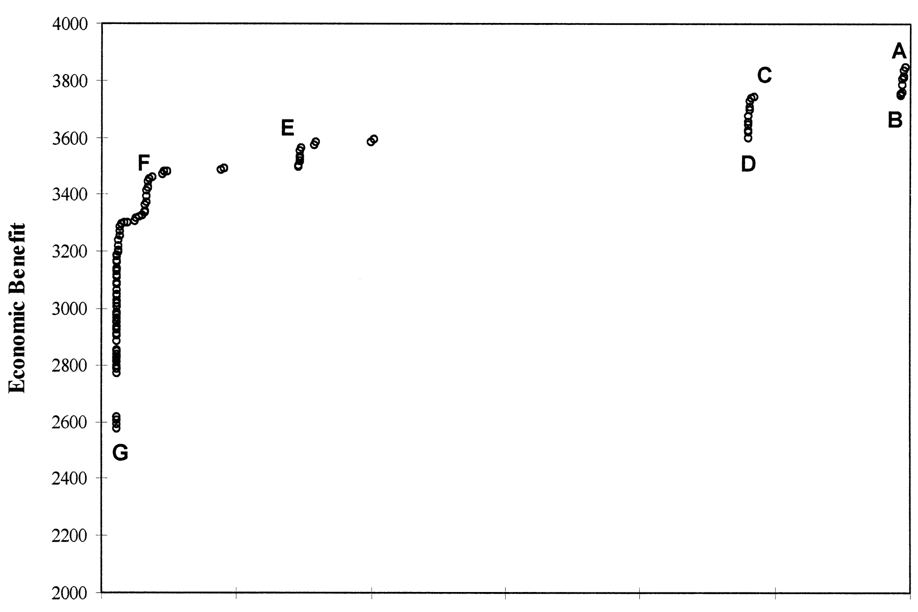

Fig. 2. Efficient frontier for expansion according to alternative K2. PLL is expected number of fatalities during plant’s lifetime. Economic benefit in MU.

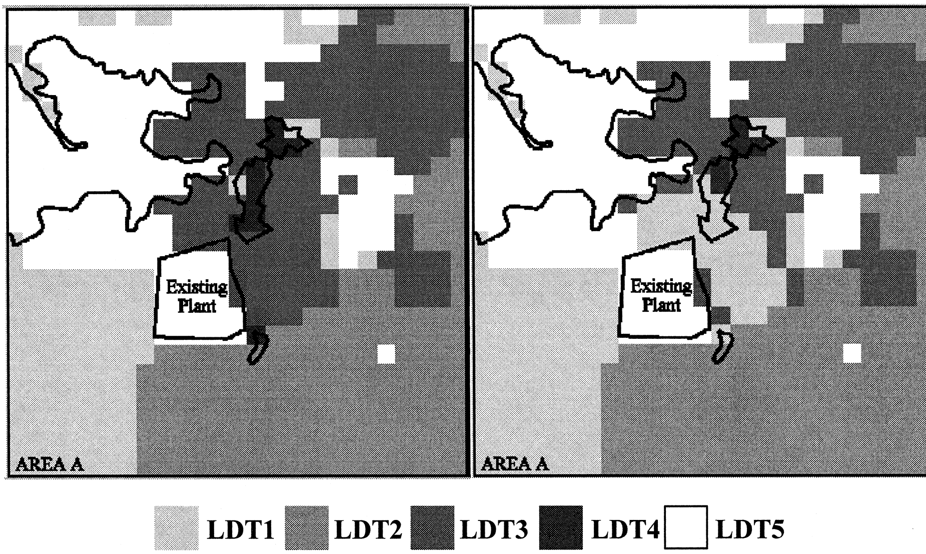

Fig. 3. (a) LUP corresponding to Point A of Fig. 2. (b) LUP corresponding to Point F of Fig. 2.

frontier can form the basis for a discussion on the available alternatives without formally establishing value tradeoffs. For example, it can be argued and easily accepted by the various stakeholders that solution (F) would be more preferable than solution (A) (see Fig. 2) since it implies a substantial decrease in PLL while the corresponding decrease in benefit might be judged as not equally significant. Furthermore, it could be argued that F is more preferred to G since the latter solution implies a large decrease in benefit with marginal decrease in PLL. The whole discussion can concentrate on whether the gains in PLL from the level implied by point A to the level implied by point F justifies the corresponding reduction of benefits. If the answer is affirmative and if, furthermore, further gain in PLL from F to G is judged marginal, then any solution around point F might represent an acceptable solution. These considerations can be further facilitated be the simultaneous perusal of the implied LUP by each point of the efficient frontier. This is made possible by the capability of the DSS to demonstrate the map corresponding to a chosen point in the efficient frontier.

The concept of efficient frontier can be also used to support decisions about alternative expansions or locations for hazardous facilities. Each potential expansion alternative is associated with an efficient frontier representing the available LUPs in the general area of the installation. Such a superposition is shown in Fig. 4 under the assumption that all expansion options are characterized by the same cost (= 700 MU) and hence, the same benefit. In this case, option K3 dominates the other solutions over the major part of the consequence range. It is only for very large relative values of life with respect to the potential benefit that the base case (i.e. no expansion at all) is becoming better. Alternatively, if the relative value of life suggests a solution in the region of high benefit-high PLL, then option K4 slightly surpasses option K3.

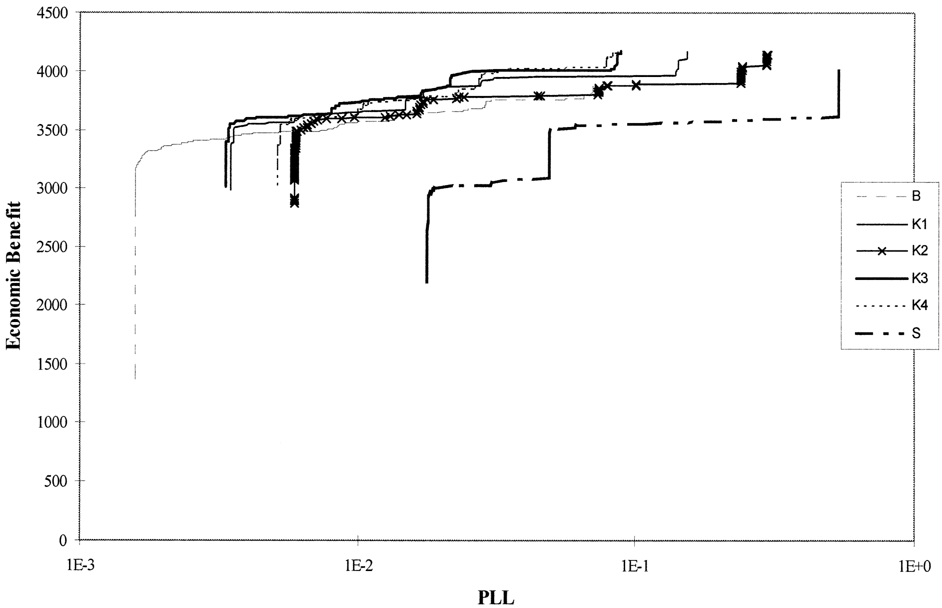

Fig. 4. Efficient frontiers for all expansion alternatives (same cost) PLL is expected number of fatalities during plant's lifetime. Economic benefit in MU.

To better demonstrate the use of multiple efficient frontiers it has been assumed that each of the alternative expansion options is characterized by a different cost and hence by a different benefit (150 MU for option S, 700 MU for options K2, K3, K4 and 650 MU for option K1). The efficient frontiers are shown in Fig. 5, while the resulting ''overall'' efficient frontier is shown in Fig. 6. Starting from point A that corresponds to the existing situation (from a population-distribution point of view) it is observed that the first few alternatives assume expansion of the refinery outside the general area of the existing facility (option S). Moving towards the direction of lower levels of PLL the optimum solutions imply expansion according to option K1, next according to option K4, then S, and then K3 alternating with K1. Finally for rather very low levels of PLL the no-expansion option becomes the preferred alternative. Note that there are no points assuming expansion according to option K2, as the efficient frontier of this expansion option is dominated by the other efficient frontiers.

A final supportive use of the efficient frontier is that of sensitivity analysis where the variation of the most preferred solution as a function of the implied value tradeoffs between benefit and potential loss of life is explored. Thus, for linear value functions, that is, a constant ''exchange rate'' between benefit and potential loss of life the following remarks can be made (see Fig. 6 and Appendix B for details on the choice of the optimum solution).

(1) Given the numerical values in the set up of the problem, the most preferred solution will be the one corresponding to point A as long as the value of life is estimated at a level less than 900 units of benefit (MU). This solution expands the refinery at another location (option S) and leaves the present uses of land as they are.

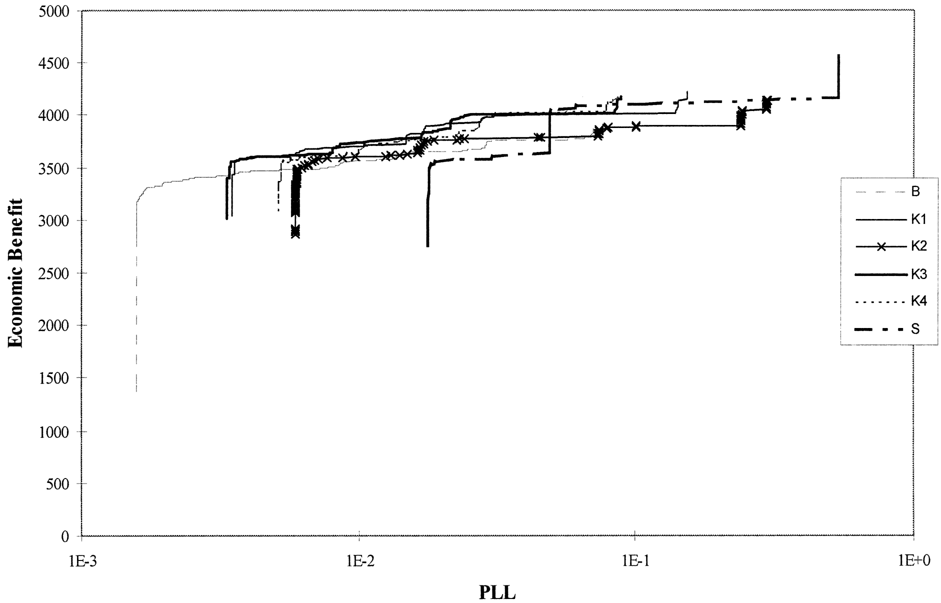

Fig. 5. Efficient frontiers for all expansion alternatives (different cost) PLL is expected number of fatalities during plant's lifetime. Economic benefit in MU.

(2) If the value of life is assessed as being higher than 900 but less than 2,800 units of benefit then the most preferred solution is the one corresponding to point C. That is,

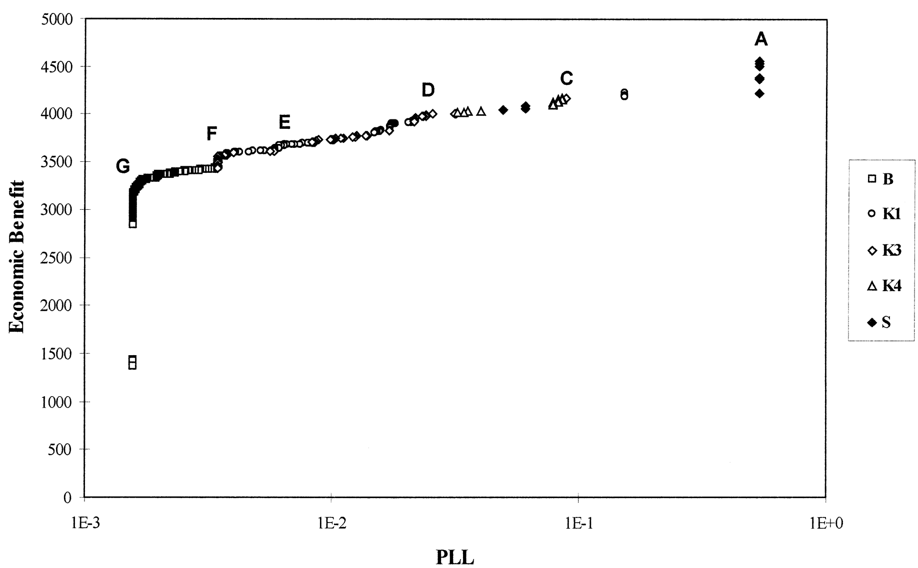

Fig. 6. Overall efficient frontier for all expansion alternatives (different cost) PLL is expected number of fatalities during plant's lifetime. Economic benefit in MU.

expand the refinery south of the existing installation and restrict the uses of land to those implied by the LUP corresponding to point C (option K4).

(3) An even higher value of life (> 2800) up to about 16,000 MU implies as best option the expansion of the refinery west of the existing installation (option K3 and point D).

(4) For values of life between 16,000 and 80,000 MU expanding the refinery south of the existing installation, but within the fence (option K1) becomes optimum with various land use restrictions depending on the particular level of value tradeoffs (up to E).

(5) Values of life higher than 80,000 but less than 145,000 imply again expansion according to option K3 (Point F).

(6) Finally, the no-expansion option (option B, point G) is preferable only if the value of life is set higher than 145,000 units of benefit. Severe restrictions over the present uses of land are also implied by such a level of exchange rate between potential loss of life and benefit.

In conclusion, it is argued that the use of the ''efficient frontier'' provides a platform that can facilitate the discussion between the various stakeholders in deciding on the preferred land use policy around hazardous installations. In particular, the proposed approach can remove from the debate a large number of ''what if'' questions since it can explore a very large number of alternative solutions and keep only those that can not

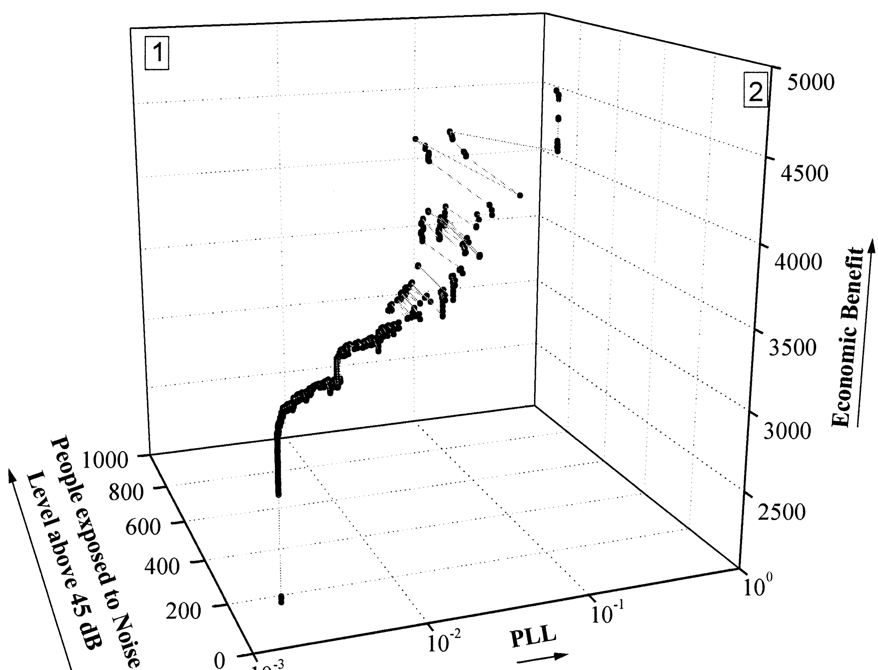

Fig. 7. Overall efficient frontier for all expansion alternatives (different cost) with three criteria PLL is expected number of fatalities during plant's lifetime. Economic benefit in MU.

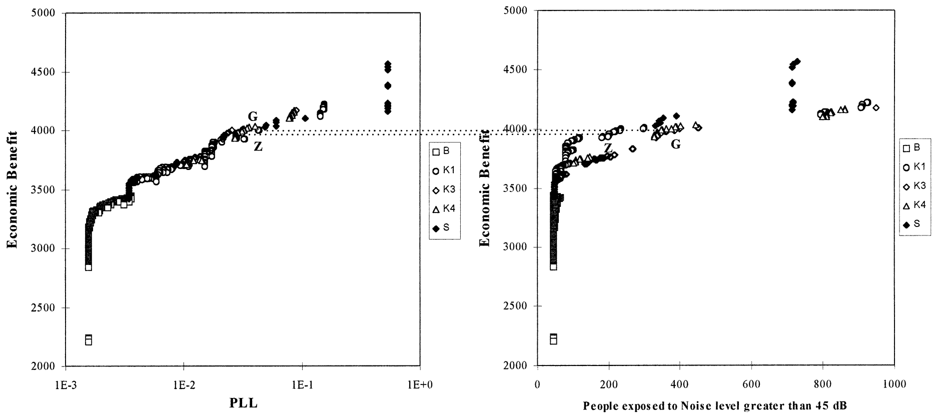

Fig. 8. 2-D projections of the overall efficient frontier for all expansion alternatives (different cost) with three criteria PLL is expected number of fatalities during plant’s lifetime. Economic benefit in MU.

be rejected on ‘‘technical’’ or ‘‘scientific’’ arguments. Perusal of the efficient frontier can then narrow the discussion to potential solutions in a specific narrow range of it, where the actual choice might also include ‘‘sub-optimal’’ solutions that include other intangible considerations not included in the quantified analysis.

4.2. Perusal of the efficient frontier with three attributes

When the number of people exposed to noise above the 45 dB level is added as a third criterion, the efficient frontier is a collection of points in the new 3-D consequence space (see Fig. 7). Visualization now is more difficult than the 2-D case but it can be

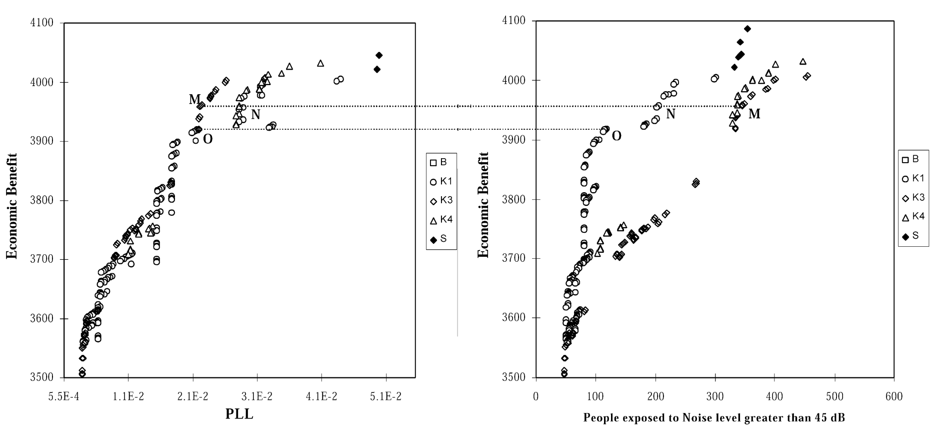

Fig. 9. Part of the overall efficient frontier for all expansion alternatives (different cost) with three criteria PLL is expected number of fatalities during plant’s lifetime. Economic benefit in MU.

facilitated if done in two 2-D projections in the benefit–PLL plane (marked as 1 in Fig. 7, see Fig. 8a) and in the benefit–noise plane (marked as 2 in Fig. 7, see Fig. 8b).

Fig. 8 provides the 2-D projections of the overall efficient frontier over the six alternative options. As expected, the efficient frontier contains all efficient solutions in two dimensions plus additional ones, which although inefficient with respect to the criteria of benefit and PLL are performing better with respect to noise. For example, point Z (PLL $= 3.2 \times 10^{-2}$, economic benefit = 3921, people exposed to noise above 45 dB = 180) is an inefficient solution with respect to benefit and PLL, when compared to point G (3.1×10^{-2}, 4000, 377). But the former is better than the latter in the noise

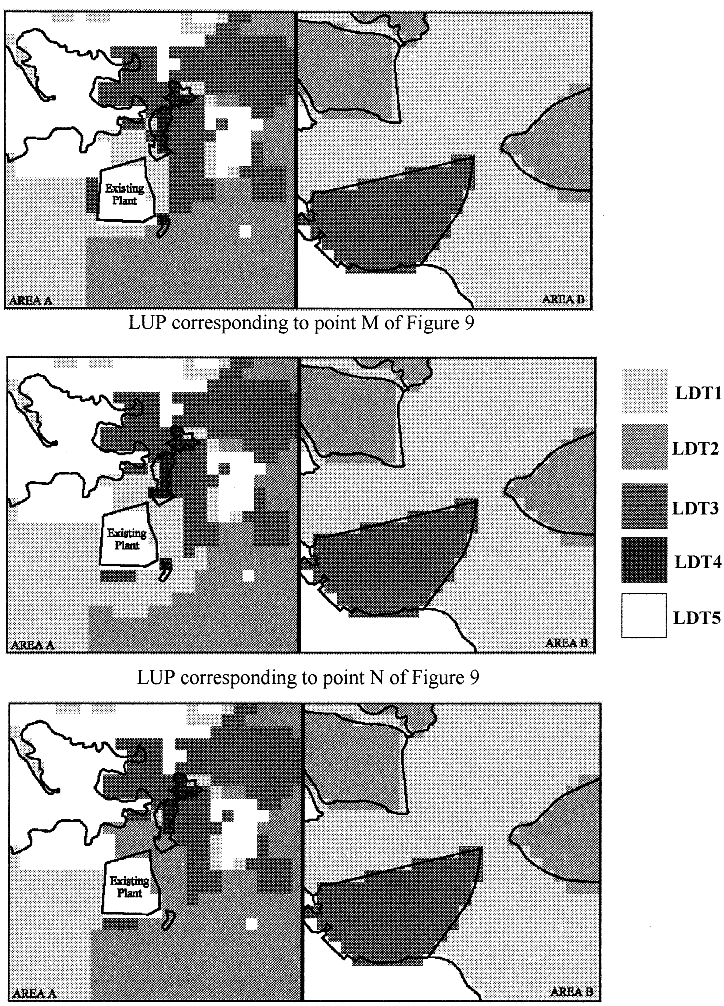

Fig. 10. LUPs corresponding to points M, N and O of Fig. 9.

criterion since it allows for only 180 people to be exposed to a noise level above 45 dB compared to 377 for point G.

Perusal of the efficient solution in three dimensions could follow the same lines as for the 2-D case. For example, assuming that benefit and PLL are considered more important than noise a discussion similar to that presented in Section 4.1 could be made on the benefit–PLL plane (Fig. 8a). Let us suppose that such a discussion resulted in a choice of a solution in the neighborhood of point M (2.2×10^{-2}, 3957, 346) (see Fig. 9).

This solution and the associated LUP (see Fig. 10) are satisfactory with respect to the achieved benefit and PLL but it exposes a rather large number of people to a high level of noise. Alternative solutions are available, however, exhibiting the same benefit but lower number of people exposed to a high noise level [e.g. point N (2.8×10^{-2}, 3953, 203)]. If the achieved improvement in the noise criterion is considered as worthwhile the increase in the PLL, point N could be selected or point O (2.1×10^{-2}, 3916, 115) with even better performance in the noise attribute. It is noteworthy that in general, expansion option K3 (in the area of point M) allows for less risky but much 'noisier' LUPs (see Fig. 9). It is also noteworthy that a discussion like this is not being made only on the basis of the efficient frontier but also having the convenience simultaneously view the LUP associated with each selected point. Fig. 10 presents the LUPs, associated with points M, N and O.

Finally, a similar, albeit more involved sensitivity analysis is possible for the three criteria case, under the assumption of additive utility function. The additivity assumption is equivalent to a constant value for each expected loss of life and a similarly constant value per person exposed to a level of noise above the limit of 45 dB (from now on referred to as 'value of noise'). Constant value of life means that each extra death is

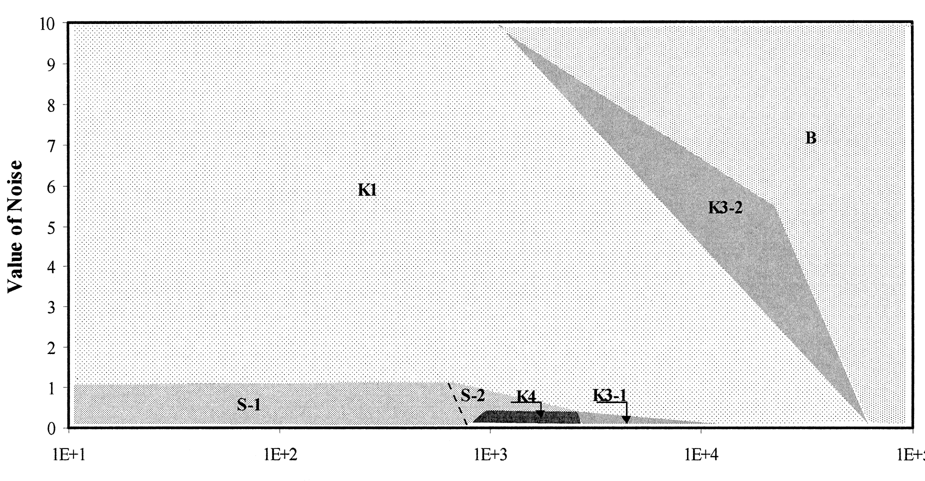

Fig. 11. Sensitivity analysis on the selection of the optimum LUP based on the efficient frontier with three criteria (in Fig. 7).

worth the same regardless of the number of deaths to which this extra death is added. Similar considerations are of course valid for the constant 'value of noise'. Under these assumptions, given a particular pair for the value of life and the value of noise, the most preferred solution can be determined from the efficient frontier. Similarly if a point in the efficient frontier is chosen, a particular pair of values for life and noise is established. The results of this analysis are shown in Fig. 11. Details on the method used to produce these results are presented in Appendix B. It is noteworthy that some very general conclusions can be drawn.

(1) Expansion solution K1 is the most preferred if the value of life is less than 900 MU and the 'value of noise' is higher than 1 MU. Several LUPs following this expansion option are optimum depending on the exact values of life and noise, the most common of which being the one corresponding to point O of Fig. 9 and shown in Fig. 10.

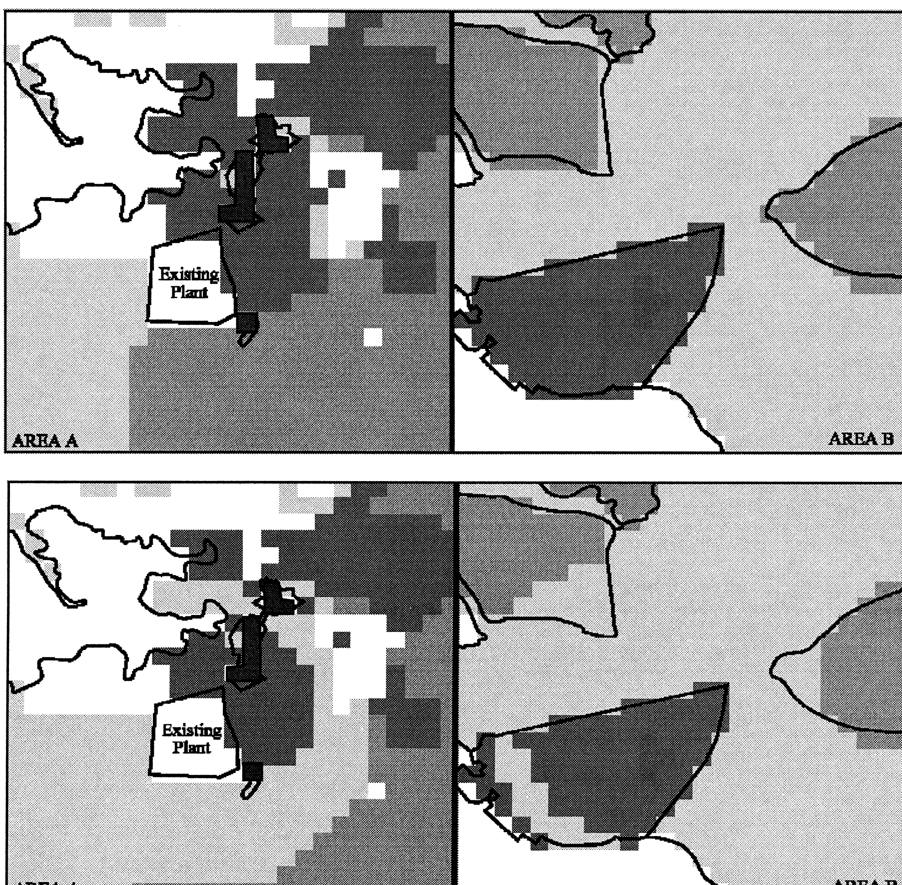

Fig. 12. LUPs corresponding to optimum points following expansion alternative S (S-1 and S-2).

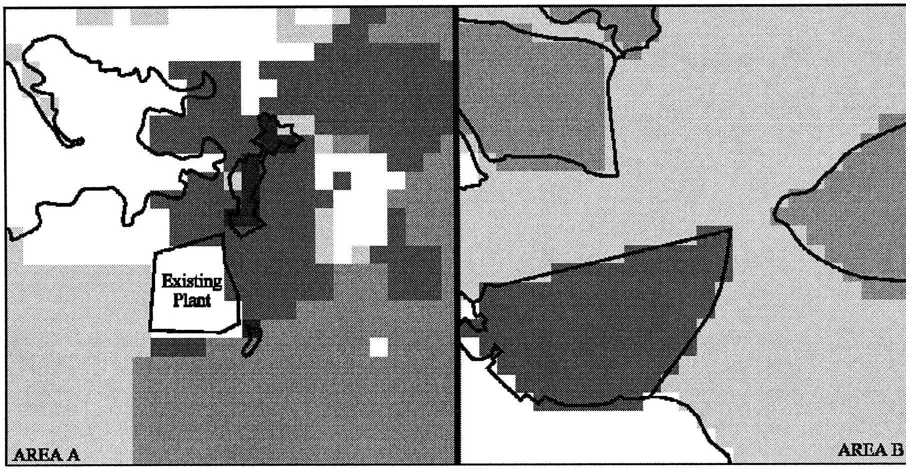

Fig. 13. LUP corresponding to optimum point following expansion alternative K4.

(2) For low 'values of noise' (i.e. two criteria decision, as in Section 4.1) the best expansion policy depends on the value of life. If the value of life is lower than 900 MU then expansion S is the most preferred (area S-1 in Fig. 10). If the value of life is between 900 and 2800 MU then another LUP following expansion S is the most preferred (area S-2). These two LUPs are shown in Fig. 12. In the same region of value of life (900 to 2800 MU) but for *very* low 'values of noise' (below 0.5, area K4 in Fig. 11), expansion K4 is the most preferred and the corresponding LUP is shown in Fig. 13. If the value of life is between 2800 and 16,000 MU (area K3-1 in Fig. 11) then

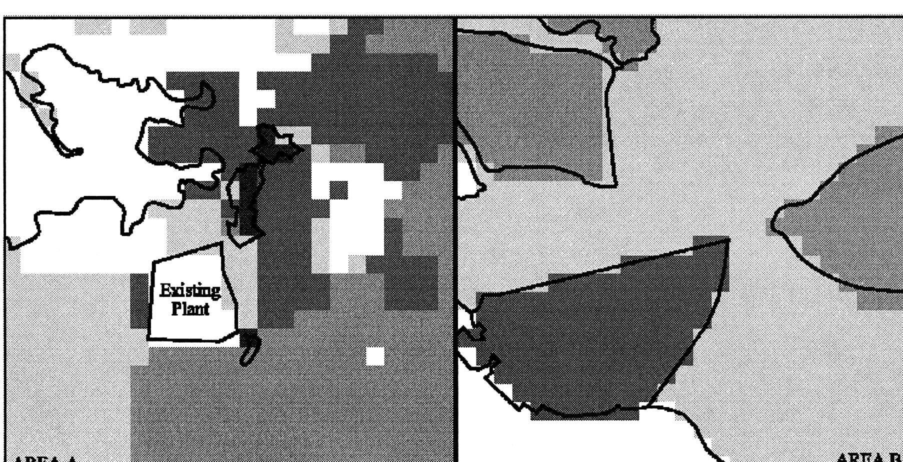

Fig. 14. LUP corresponding to optimum point following expansion alternative K3-1.

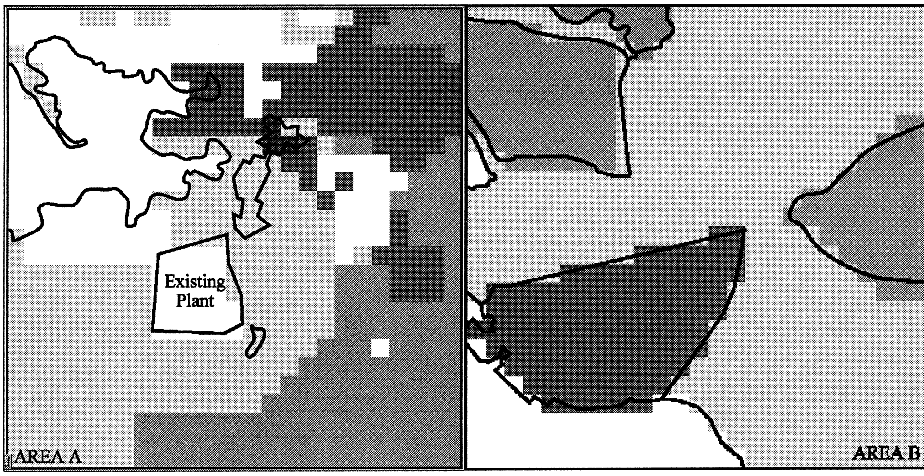

Fig. 15. LUP corresponding to optimum point following expansion alternative B.

expansion K3 is the most preferred, the corresponding LUP being shown in Fig. 14. If the value of life is between 16,000 and 80,000 MU then expansion K1 is again the most preferred. For values of life greater than 80,000 MU as well as for the whole area defined as area B in Fig. 11, the ‘no expansion’ alternative is the most preferred and the corresponding LUP is shown in Fig. 15.

(3) Finally, for values of life and noise in the area defined as area K3-2 in Fig. 11, expansion K3 is the most preferred and the corresponding LUP is shown in Fig. 16.

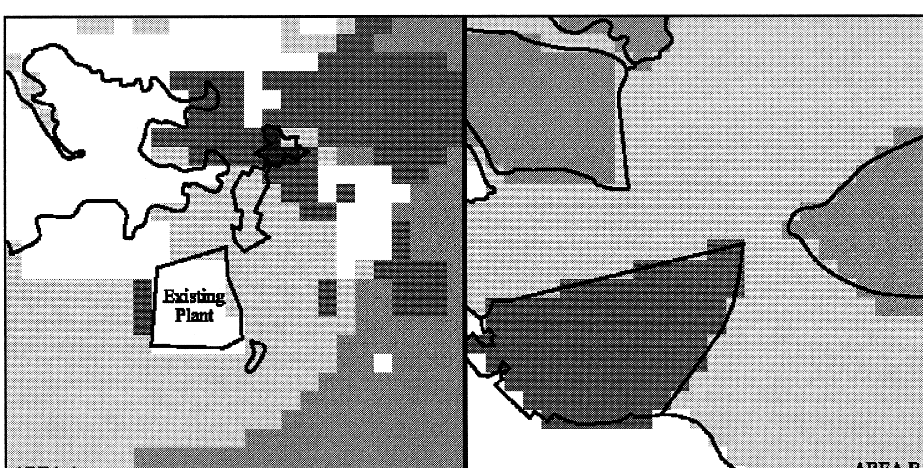

Fig. 16. LUP corresponding to optimum point following expansion alternative K3-2.

5. Discussion and conclusions

A realistic case has been considered in the framework of the LUPACS project to test and improve a methodology for supporting decisions concerning risk management through land use planning. The objective of the case study was not to support an actual decision but rather to test the validity of and suggest improvements for the proposed methodology. Two points of views can be distinguished: those of the methodology developers and those of the planners, hereafter collectively called ‘methodology team’ and ‘end users’, respectively. The conclusions presented here are those of the ‘methodology team’.

- As far as the decision space is concerned, the methodology is capable of generating a very rich set of alternative LUPs and an adequate number of alternative sites for hazardous installations. All particular concerns of the ‘end users’ were taken into consideration. One issue in need of further research is potential constraints on the use of land as, for example, the requirement of specific minimum percentages for certain uses of land. The case study also affirmed the need for free-shape cells.
- With respect to the set of objectives and attributes the methodology had no problem to accommodate all end-users concerns. One drawback, inherent to all MCDA approaches, is the proliferation of attributes. In order to be able to use the main advantage of the proposed approach, that is determination of alternatives at the level of cells, generation of efficient solutions and perusal of the efficient set with a simultaneous view of the corresponding LUP, the number of attributes can not be larger than five. For more than five attributes, only very experienced analysts can follow the projections of the efficient frontier. There is a need, therefore, for identification of a few proxy attributes representing the major areas of concern.
- Preference structure was of non-apparent concern to the end users. Adequacy of linearity and additivity were not questioned during this case study. Exploration of risk aversion attitudes is possible but not addressed in this case. A general question of alternative algorithms for the generation of the efficient frontier under broader assumptions remains an open issue.
- Perusal of the efficient frontier has been found very useful by the methodology team, particularly, for reaching rather general conclusions. An issue of concern with the ‘end users’ was the great number of the remaining efficient solutions. The algorithm has the capability of generating only those efficient solutions that differ by more than a given amount in the various attributes. This capability should be always used to concentrate the discussion on limited number of options. An additional feature judged necessary for the associated DSS rather than the methodology itself, was the capability to examine ‘inefficient’ solutions. Given a particular point in the consequence space and the associated LUP one is often interested in altering the characteristics of the LUP and in knowing the consequences of the new alternative. This way even (more or less) inefficient solutions might be chosen owing to concerns not explicitly expressed through the adopted set of attributes.
- The overall reception of the methodology by the end users can be considered ‘lukewarm’. This is partially due to the background of the ‘end users’ (social scientists and fire fighters in their overwhelming majority) who in some instances had problems

grasping a 2-D graph. Another difficulty came form the novelty of the risk issue to most ‘end users’. As a result, most of the time the two teams were together, was spent in discussion of fundamental concerns and concepts, one team trying to transfer to the other their corresponding experience using a new language. One major conclusion was, therefore, that a very systematic educational effort by experience facilitators is necessary before the virtues of the proposed methodology can be appreciated in a real case.

Acknowledgements

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Appendix A. The decision support system

To implement the methodology described above, a DSS using a Graphical User Interface (GUI) was developed, the main features of which are as follows.

First, the user has to provide the criteria that will be used, along with the desired direction of their values (i.e. whether minimization or maximization is desired for each criterion).

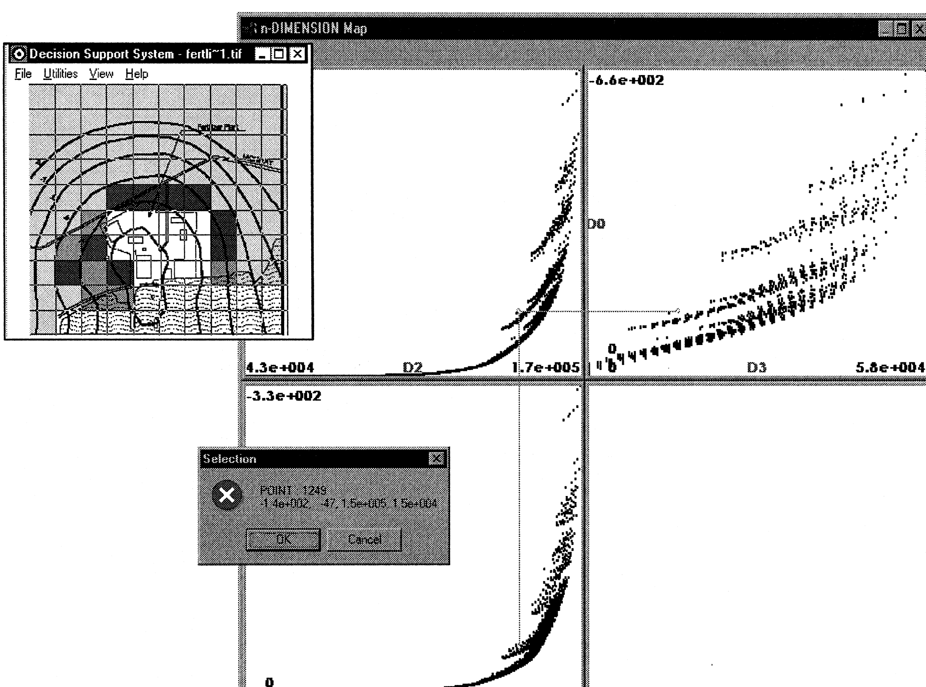

Fig. 17. Screenshot of the DSS GUI.

Then, the different LDTs that can be applied to each cell must be defined, along with the population densities for each LDT.

Finally, the values of each criterion (other than PLL, which is calculated as a function of the population densities already input and the IR profile, which is also input to the DSS) for each LDT and for each cell are input.

At this stage, input is complete and the tool proceeds with the generation of the efficient frontier.

This efficient frontier can be observed and studied leading to conclusions as those described in Section 4, using the last part of the DSS which is shown in Fig. 17. Fig. 17 is a screenshot of the DSS and one can see the 2-D projections of the consequence space. The user can zoom in or out those 2-D projections in order to find a specific point in the consequences space. Once a point is selected its coordinates on the consequence space are presented (the values of the criteria). The LUP (the point in the decision space) corresponding to that point gets automatically presented. As described in Section 2.1, every LUP is formed when every cell has been assigned a unique LDT. Thus, each cell on the map of the area (in the upper left corner of Fig. 17) gets colored according to its LDT.

Appendix B. Choice of the optimum solution

Given the additivity assumption (additivity independence, see Ref. [2]), the utility function for a 2-D consequence space is given by

$$u(\mathrm{PLL},\mathrm{EB}) = k u_{\mathrm{PLL}} + (1-k) u_{\mathrm{EB}} \tag{1}$$

where k is a relative importance coefficient taking values in the interval (0,1), u_{PLL} is the utility function for PLL, and u_{EB} is the utility function for economic benefit.

The risk neutral attitude towards the attributes PLL and EB implies linear utility functions u_{PLL} and u_{EB}. That is:

$$u_{\mathrm{PLL}} = \frac{\mathrm{PLL}_{\mathrm{MAX}} - \mathrm{PLL}}{\mathrm{PLL}_{\mathrm{MAX}} - \mathrm{PLL}_{\mathrm{MIN}}} \tag{2}$$

giving $u_{\mathrm{PLL}} = 0$ when $\mathrm{PLL} = \mathrm{PLL}_{\mathrm{MAX}}$ and $u_{\mathrm{PLL}} = 1$ when $\mathrm{PLL} = \mathrm{PLL}_{\mathrm{MIN}}$.

Similarly,

$$u_{\mathrm{EB}} = \frac{\mathrm{EB} - \mathrm{EB}_{\mathrm{MIN}}}{\mathrm{EB}_{\mathrm{MAX}} - \mathrm{EB}_{\mathrm{MIN}}} \tag{3}$$

giving $u_{\mathrm{EB}} = 0$ when $\mathrm{EB} = \mathrm{EB}_{\mathrm{MIN}}$ and $u_{\mathrm{EB}} = 1$ when $\mathrm{EB} = \mathrm{EB}_{\mathrm{MAX}}$.

The point of the efficient frontier maximizing the utility function $u(\mathrm{PLL},\mathrm{EB})$ is the most preferred. Mathematically, this is obtained when

$$\frac{\mathrm{d}u(\mathrm{PLL},\mathrm{EB})}{\mathrm{dPLL}} = 0 \tag{4}$$

By virtue of Eqs. (1)–(4), it follows that

$$\alpha = \frac{\mathrm{dEB}}{\mathrm{dPLL}} = \frac{k}{1-k} \frac{\mathrm{EB}_{\mathrm{MAX}} - \mathrm{EB}_{\mathrm{MIN}}}{\mathrm{PLL}_{\mathrm{MAX}} - \mathrm{PLL}_{\mathrm{MIN}}} \tag{5}$$

The value of α is what is being referred to as 'value of life' in Sections 4.1 and 4.2.

Substituting Eqs. (2), (3) and (5) into Eq. (1) gives:

$$u(\mathrm{PLL,EB}) = \frac{\alpha(\mathrm{PLL}_{\mathrm{MAX}} - \mathrm{PLL}) + (\mathrm{EB} - \mathrm{EB}_{\mathrm{MIN}})}{\alpha(\mathrm{PLL}_{\mathrm{MAX}} - \mathrm{PLL}_{\mathrm{MIN}}) + (\mathrm{EB}_{\mathrm{MAX}} - \mathrm{EB}_{\mathrm{MIN}})} \tag{6}$$

For a given value of life α, the doublet (PLL,EB) that maximizes u(PLL,EB) in Eq. (6) corresponds to the most preferred solution of the efficient frontier. For a range of values of α, the same solution might be the optimum one depending on the shape of the efficient frontier. Those ranges are the ones presented in Section 4.1.

For three attributes (PLL,EB,PN), where PN is 'people exposed to a noise level above 45 dB', the corresponding equation is,

$$u(\mathrm{PLL,EB,PN}) = \frac{\alpha(\mathrm{PLL}_{\mathrm{MAX}} - \mathrm{PLL}) + (\mathrm{EB} - \mathrm{EB}_{\mathrm{MIN}}) + \beta(\mathrm{PN}_{\mathrm{MAX}} - \mathrm{PN})}{\alpha(\mathrm{PLL}_{\mathrm{MAX}} - \mathrm{PLL}_{\mathrm{MIN}}) + (\mathrm{EB}_{\mathrm{MAX}} - \mathrm{EB}_{\mathrm{MIN}}) + \beta(\mathrm{PN}_{\mathrm{MAX}} - \mathrm{PN}_{\mathrm{MIN}})} \tag{7}$$

The value of β is what is being referred to as 'value of noise' in Section 4.2.

For a given value of life α and a given value of noise β, the triplet (PLL,EB,PN) that maximizes u(PLL,EB,PN) in Eq. (7) corresponds to the most preferred solution of the efficient frontier. For a range of values of α and β, the same solution might be the optimum one depending on the shape of the efficient frontier. Those ranges are the ones presented in Section 4.2 and shown in Fig. 11.

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