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# ADVANCED DECISION-ORIENTED SOFTWARE FOR THE MANAGEMENT OF HAZARDOUS SUBSTANCES

## PART VI:
## The Interactive Decision-Support Module

Ch. Zhao
L. Winkelbauer
K. Fedra

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INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
2361 Laxenburg, Austria

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## PART VI: The Interactive Decision-Support Module

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## 1. INTRODUCTION: MODEL-BASED DECISION SUPPORT

After the generally perceived failure of computer-based information systems to provide the information needed by strategic decision makers, many researchers have recognized the potential of decision support systems as a remedy for this problem. A decision support system is most commonly directed toward providing structured information to managers faced with those ill-structured problems that are typical of strategic planning and decision making.

From a decision support or decision analysis point of view, the major components of a decision situation are:

- a set of feasible alternatives, or courses of action open to the decision maker, described in terms of decision-relevant criteria and auxiliary descriptors;

- a set of goals or objectives that the decision, i.e., the selection of any one alternative, has to contribute to;
- a value system, implicit or explicit, that describes the relative importance of criteria in respect to each other as well as the contribution of certain criteria values towards the respective goals or objectives.

Depending on the level of detail, real-world alternatives in the domain of large and complex socio-technical systems such as the area of hazardous substances management addressed in the context of this study (Fedra, 1985; Fedra and Otway, 1985) are usually very complicated, i.e., rich in detail, and complex, i.e., rich in structure and relationships. Their extensive description, let alone their thorough evaluation, is a formidable task, far beyond the intellectual capabilities of any individual.

Modern information technology can certainly help to organize this wealth of information; data bases as well as models simulating the underlying processes and relationships are powerful tools in structuring and organizing complex information. Simulation models can generate alternatives and estimate many of the criteria necessary for their comparative evaluation. The comparative evaluation itself and the eventual decision, however, require experience and judgement as well as the information basis provided by the appropriate information technology.

Thus, to support policy and management decisions, it is important to provide **substantive background information** in the form of easily accessible data bases, as well as models **and** tools for **interactive decision support**. Finally, the user or decision maker must be allowed to exert a high level of control over the software, and he must be able to bring his experience, judgement and discretion to bear in a substantial way. The system must be easy to use, easy to understand, and responsive. Clearly, tools to meet the above requirements have to be tightly coupled, and integrated into one coherent decision support system. This would allow one to iteratively generate as well as to subsequently evaluate and select alternatives from the set generated, and described by a comprehensive list of criteria.

In this paper we introduce an interactive, display-oriented postprocessor for multiobjective selection or discrete optimization, which has been implemented within the framework of a project on Advanced Decision-

Oriented Software for the Management of Hazardous Substances (Fedra, 1985).[*] The approach and software described here is designed as a tool to improve the usefulness and usability of decision support systems through the easy access to a rich set of powerful support functions and display options, and tight integration with substantive models and data bases. At the same time it adds a new dimension of usefulness to the simulation models it is connected to as an output post-processor, aiding in the comparative evaluation of complex modeling results.

### 1.1 Background: Hazardous Substances Management

Many industrial products and residuals such as hazardous and toxic substances are harmful to the basic life support system of the environment. In order to ensure a sustainable use of the biosphere for present and future generations, it is imperative that these substances are managed in a *safe and systematic* manner. The framework system (Fedra, 1985) is designed to provide software tools which can be used by those engaged in the management of the environment, industrial production, products, and waste streams, and hazardous substances and wastes in particular.

The system consists of an *integrated set of software tools*, building on existing models and computer-assisted procedures. This set of tools is designed for non-technical users.

To facilitate the access to complex computer models for the casual user, and for more experimental and explorative use, it also appears necessary to build much of the accumulated knowledge of the subject areas into the user interface for the models. Thus, the interface incorporates elements of a knowledge-based expert system, that is capable of assisting any non-expert user to select, set up, run, and interpret specialized software. By providing a coherent user interface, the interactions between different models, their data bases, and auxiliary software for display and analysis become transparent for the user, and a more experimental, educational

[*] This software system for the management of hazardous substances and industrial risk is developed under contract to the Commission of the European Communities (CEC), Joint Research Centre (JRC), Ispra, Italy.

style of computer use can be supported.

One important part of the applications of the framework system is *scenario analysis*, i.e., within the context of one or a group of linked simulation models, the user defines a scenario, i.e., a set of assumptions, boundary conditions and control variables describing a specific problem situation (e.g., the transportation of a certain amount of a hazardous chemical substance from a supply point, the industrial plant or chemical deposit, to a demand point) and then traces the consequences of this situation through modeling. In scenario analysis, the consequences of the settings of control variables and parameters, describing control or policy options, as well as external driving forces, each set defining one scenario, are estimated in the form of complex data which represent the answer to the user's question: "What, if ... ?".

Usually the consequences of each set of assumptions analyzed are quantifiable, that is, they can be measured on some natural or artificial, numerical or descriptional scales. Quantified and, if necessary, aggregated attributes become criteria, which in most cases are incommensurable (e.g., cost and risk), discrete and finite. They are discrete and finite, because for many real world problems continuous variables are not meaningful (e.g., trucks come only in a limited number of sizes, and they can have only one, two or maybe three, drivers) the values for some criteria come directly from experts (e.g., criteria of an aesthetic or political nature and should be expressed as a few classes rather than on an arbitrarily "precise" scale), the set of feasible and meaningful control and policy options is usually finite and small, and because scenario analysis is restricted to a finite number of simulation runs.

To evaluate the outcomes from different scenarios on control and policy alternatives, to present complex data such that direct comparison is supported, and finally to select the alternative which "best" suits the client's preferences, it is necessary to provide a tool for implicit optimization, i.e., multicriteria decision analysis.

# 2. RISK-COST ANALYSIS MODEL FOR THE TRANSPORTATION OF HAZARDOUS SUBSTANCES

A Risk-Cost Analysis Model for the Transportation of Hazardous Substances (Kleindorfer and Vetschera, 1985) has been implemented as one of the simulation and decision support models within the overall framework system.

The model is based on

- a geographical representation of a given region (e.g., of Europe) which specifies supply and demand points together with various routes connecting these points,
- on regulatory policies such as risk minimization and
- on economic policies such as cost minimization.

The function of this model is to enable the user to solve the problem of choosing the "best" route and mode for the transportation of hazardous substances from a certain supply point to a certain demand point, and in defining policies that ensure the selection of these mode/route alternatives.

## 2.1 Overall Structure of the Model

The model is designed as a policy-oriented tool. Its structure therefore, has to closely follow the structure of decision variables open to regulators. In general we can distinguish two different levels at which regulations might operate:

- a *micro level*, dealing with individual transport activities or connections,
- an *aggregated level* aiming at global regulations that can be applied to a large class of shipments.

The model currently implemented in the framework system concentrates on the **micro level decision problem**, e.g., individual shipments of hazardous substances.

For analysis at the micro level the model will generate and evaluate possible transportation alternatives for a given transport objective. A transport objective is defined by the amount and type of hazardous substance to be transported and the points between which the goods are to be transported.

A transport alternative in the model is represented by a geographical route along which the transport is to occur and the choice of a transport mode, both associated with risk-cost criteria. The possibility of mode changes along the route is also considered in the model.

A detailed cost and risk analysis for all the alternatives generated is then performed and the results of this evaluation are presented to the decision maker for his final choice among the alternatives using the Interactive Data Post Processor.

From the perspective of software engineering the implementation of the model consists of three main modules (Figure 2.1).

- The first module generates candidate paths and consequently generates different route/mode combinations. To limit the amount of alternatives to reasonable numbers, the search area is restricted.
- The second module performs a risk-cost evaluation of the paths generated in the first phase. The outcome of the second phase is a list of criteria values of all the alternatives for further evaluation.
- The third module selects the "best" transportation alternative with respect to the criteria specified by the decision maker and the preferences expressed.

In most cases the number of alternatives is large and the selection of a preferred alternative from the set of feasible alternatives generated will require computer-assisted information management and decision support.

## 2.2 Model Input

The data structure of the Risk-Cost Analysis Model for the Transportation of Hazardous substances consists of four main parts:

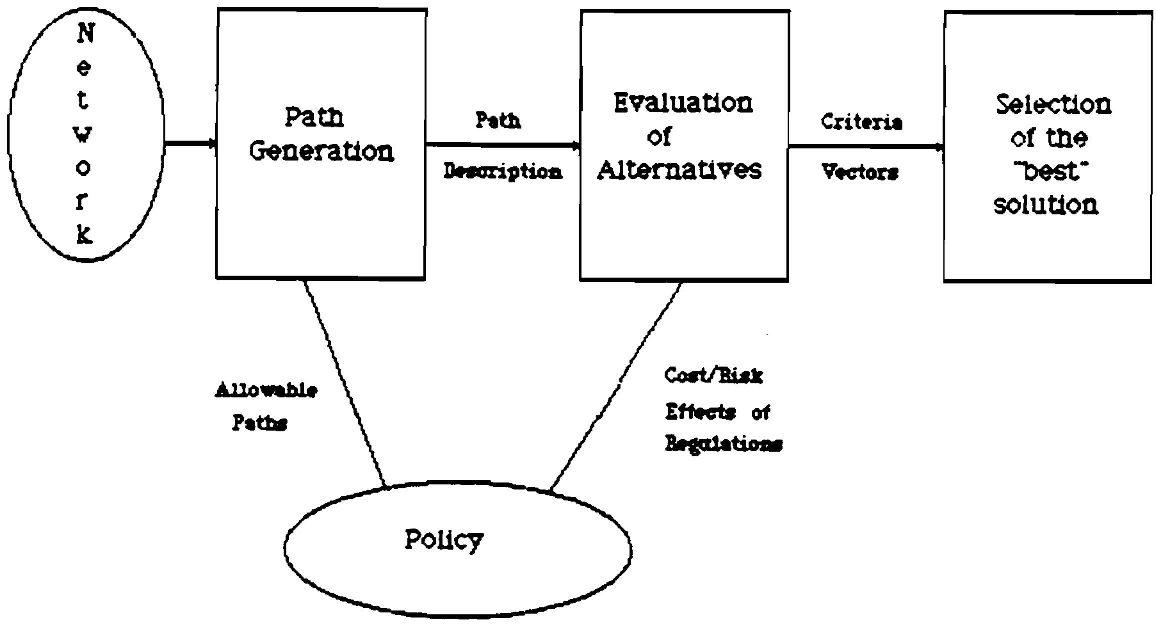



*Figure 2.1: Overall structure of the transportation model*

- a description of the transportation network, i.e., the cities and the links between them,
- risk indicators,
- cost factors,
- general information about the model.

The *general information* about the model is represented by the following elements:

- substances to be transported, described by their specific gravity,

- a description of the *descriptors* of the arcs,
- a list of risk groups: damages, injuries and deaths,
- a list of land usage classes: urban, suburban and agricultural,
- the vehicles (i.e. trucks, cars, trains, etc.), described by capacities.

The *transportation network* is described as follows:

The *nodes* describe the cities by their relative coordinates.

The arcs describe the links between the cities, e.g., the road or rail system by their

- length,
- mode (e.g., road, railroad, etc.)
- descriptors (e.g., tunnel, bridge, etc.)
- type (e.g., highway, minor road, etc.)
- shares of land usage class, i.e., the kind of environment (e.g., urban, suburban, agricultural) the road or rail passes through.

Based on this data structure initially all possible paths (within a heuristically defined "window") are generated for each vehicle under consideration from the specified support point to the specified demand point.

For these paths risk and cost are estimated, and finally they are compared and evaluated.

## 2.3 Evaluation of Alternatives

Alternatives are evaluated in terms of cost and risk. The criteria of cost and risk are incommensurable; for instance, the cost of transportation is measured in monetary value and the risk of transportation is measured in the number of fatalities in the event of an accident.

Sometimes cost and risk are contradictory, for example the shortest – and thus usually the most cost-effective – connection is a highway that passes close to densely populated areas, with a higher risk potential than more remote, and therefore more expensive routes.

In this model cost evaluation is based on freight rate sampled from commercial transport firms. The cost function is simply described by the following formula.*)

$$C = c_f + (c_0 + c_s * X) * L$$

where

$c_f$: fixed costs

$c_0$: initial part of the variable costs function

$c_s$: slope of the variable costs function

X: amount of substance to be shipped

L: length of the path.

The risk analysis in the model covers both losses in the form of property damage and losses in the form of injuries and fatalities. Considering the stochastic nature of these losses expected values and the variance of losses are taken as decision criteria.

A simplified lognormal distribution risk analysis submodel is employed to evaluate the alternatives. As outcomes of risk analysis, the criteria of alternatives are described in terms of expected losses and variance of losses to a given group along a route in the network. Further on, the groups of objects that can be affected by accidents (population, property values etc.) will be represented by g.

The formulations of these criteria are as follows. The expected loss $E[R_g]$ of group g along route $(r_1, r_2, \ldots, r_l)$ is :

$$E[R_g] = \sum_{i=1}^{l} \prod_{k<i} (1 - p_a(r_k)) \cdot p_a(r_i) \cdot \sum_{n=1}^{N} q_n \cdot e^{\mu_n + \frac{1}{2}\sigma_n^2}$$

*) This cost function is only a very crude first approximation and strictly speaking only valid when the volume to be shipped is very large in relation to the capacity of any vehicle to be used. Also, the linear distance dependency only holds for relatively large distances.

where

$p_a(r_k)$: the probability of an accident on arc k

$q_n$: the probability of an accident, which happens for type n land usage on arc r

$\mu_n$, $\sigma_n^2$: parameters of lognormal distribution of conditional density function for type n.

The variance of losses to a given group g along route $(r_1, r_2, \ldots, r_l)$ is :

$$var(R_g) = E[R_g^2] - E[R]^2$$

where

$$E[R^2] = \sum_{n=1}^{N} q_n . e^{2.(\mu_n + \sigma_n^2)}$$

and

$$E[R_g^2] = \sum_{i=1}^{l} \prod_{k<i} (1 - p_a(r_k)) \cdot p_a(r_i) \cdot \sum_{n=1}^{N} q_n . e^{2.(\mu_n + \sigma_n^2)}$$

Both the expected value and the variance of losses to several groups are characteristic of a route/mode combination that will be used in evaluating the different alternatives. For three risk groups (property damage, fatal and non-fatal injuries) six risk-related objectives can be considered in the evaluation.

Combining these six objectives with cost, we can get a well-defined multiobjective decision problem with seven criteria.

To simplify our description, further on the problem with only three criteria (cost, expected loss i.e., property damage, and expected number of fatalities) will be considered as an example.

### 2.4 Model Output

The output of the transportation model consists of a list of criteria for all the alternatives:

The *risk indicators* are represented as follows:

- risk groups (e.g., damages, injuries, deaths);
- possibilities of accidents (a priori);
- consequences of an accident, depending on the substance involved, land usage class and risk group.

The *cost factors* are described by the following variables:

- transport costs, fixed and variable,
- insurance costs, depending on the type of arc and the transportation medium used.

## 3. SOME EXAMPLES OF MICROCOMPUTER-BASED DECISION ANALYSIS SOFTWARE

*Support for the decision making process is typically present in three general forms. First, the DSS [Decision Support System] should provide accurate, timely information which supports the intelligence phase of decision making. Second, the DSS should assist in designing alternative courses of action. The DSS may develop alternatives on its own, (through a goal seeking capability) and it should be able to analyze different alternatives (through a what-if capability). And finally, many decision support systems recommend a specific course of action to follow in order to support the choice phase of decision making.* (Hogue and Watson 1985)

Of course, it is not necessary for a certain decision support system to have all three supporting functions. They are important criteria in describing decision support systems. Also, for such intrinsically interactive and user-oriented software such as DSS, it is interesting to compare the user interface which is another critical criterion of practical usability.

Given below are brief descriptions and assessments for some microcomputer-based decision support systems in the market as comparative background material. These descriptions and assessments are based on the following simplified version of the transportation problem introduced in chapter 2.

The scenario under consideration is the transportation of a certain amount of a chemical substance from A to B. Five alternative pathways associated with different transportation modes are possible. As criteria for the multiobjective optimization only the cost of transportation, the expected value of losses of property damage and the expected value of the number of fatalities are considered. Let us suppose that the decision maker wants to minimize all three criteria.

### 3.1 Expert Choice

**Expert Choice** is a decision support system software package developed by Decision Support Software Inc., McLean, Virginia in 1983.

It does not propose decisions, but it helps the user to make decisions based on his judgements. Expert Choice does not restrict the judgment process to quantifiable attributes. Both quantitative and qualitative judgments are accepted.

With Expert Choice the decision maker can organize a complex decision problem in a hierarchical tree structure. This makes it possible to integrate judgements and measurements in the same hierarchical structure to achieve the "best" solution. The hierarchical tree consists of nodes at different levels. Each of these nodes in turn can have at most seven branch nodes in each of the six hierarchy levels. The goal node is at level 0; the user can define nodes at levels 1-5. Thus Expert Choice is capable of modeling very large problems (thousands of nodes).

The decision tree for our sample transportation problem is shown in Figure 3.1.

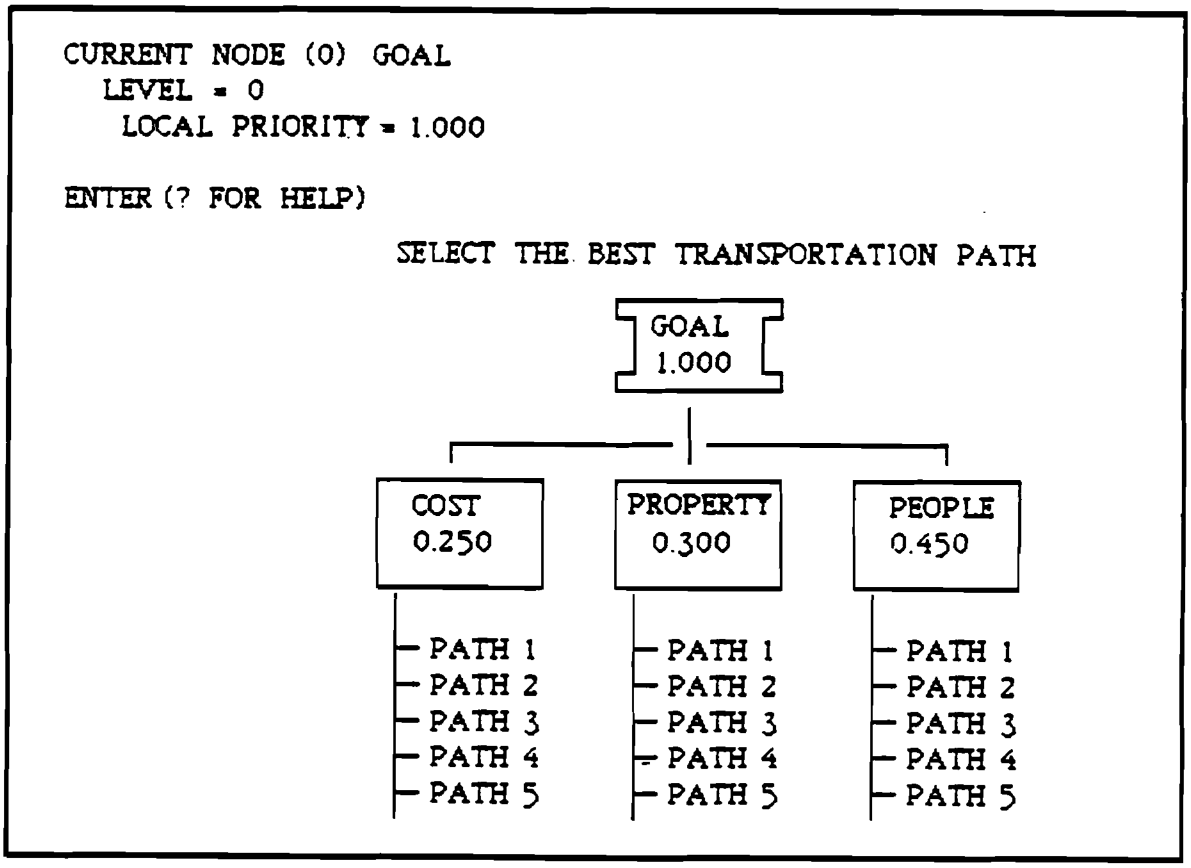



*Figure 3.1: Expert Choice decision tree for sample transportation problem*

Once the Expert Choice model is built, the user can start the judgement process. First, Expert Choice asks the user to compare the main criteria in pairs with respect to the goal in terms of importance, preference and likelihood. This is done by asking the user questions like "Do you think that with respect to the goal COST is extremely, very strong, strong, moderate or equal to PROPERTY DAMAGE ?", or – in an alternative mode – by direct input of a numerical specification to express the importance of each criterion.

The attributes of the alternatives are also determined by qualitative pairwise comparison. Expert Choice derives priorities from these simple pairwise comparison judgements. It then synthesizes or combines these priorities through weighting and obtains overall priorities for the alternatives at the bottom of the tree. This is the final result and amounts to a ranking of the alternatives, which is shown in bar charts (the alternative with the longest bar is the "best" solution).

The technique employed in Expert Choice is quite easy for the non-expert user to understand. To run Expert Choice, only the ability to compare criteria, and judgement, are required on the part of the user.

Obviously there are some disadvantages to Expert Choice. Only a rough ranking of alternatives is provided to the user and there is no background information available from other "hard" computer models in the system.

Expert Choice is most likely suitable for problems where the attributes of the problems are difficult to describe in terms of quantity. The decision recommended by Expert Choice is to a large degree based on the judgement of the decision maker.

Expert Choice requires an IBM PC-XT or similar PC.

### 3.2 MATS System

**MATS** (Multi-Attribute Tradeoff System) is an interactive decision support system to assist planners in the systematic evaluation of plans with impacts on many factors. MATS was developed at the Environmental and Social Branch Division of the Planning Technical Services Engineering and Research Center, Denver, Colorado, in 1983. The MATS program was developed to assist planners in analyzing tradeoffs between multiple objectives or attributes, in order to arrive at a judgment of the overall worth of a given mix of gains and losses for those attributes. The basic method employed in MATS is based on utility theory and the weighting coefficient method.

In our example the decision maker at first is asked to enter the criteria and their ranges (with specification of the best and worst level). Then MATS asks a series of questions in the following form: "Which change is more significant ?" followed by two change ranges (e.g. 1000 to 2000 and 5000 to 4000) to select from and one possibility to express that both changes are equal in the opinion of the decision maker. So MATS obtains the subjective weightings for the criteria from the decision maker.

After the elicitation of criteria rankings MATS produces "subjective weighted" impacts for each plan. These weighted impacts are on a common scale and can be added to arrive at a total score for each plan. According to the total score for each plan the procedure of ranking alternative plans is carried out.

After the ranking procedure the utility functions are displayed in a simple graphical style and then the alternative plans are listed on the screen in sequence of their priority, and for each of them their total plan score and their objective values, subjective values (values of the utility) and subjective weighted values are displayed.

Only "quantifiable" attributes can be evaluated by this software. The capability of the system is limited to 40 plans which can be evaluated and ranked. The system is scrolling- and not screen-oriented, and only provides menus in each interactive phase which can not give the user a visual impression of his problem, as for example, a graphics-based user interface could. The main disadvantage of MATS is that it is difficult for a user to specify his preferences in terms of weighting coefficients.

An IBM PC-XT is required to support the MATS software.

### 3.3 ARBORIST

**ARBORIST** features a graphics user interface for decision-tree construction, evaluation, and analysis. As is well known, decision-tree methodology can help a decision maker to structure and formulate preferences and choices while analyzing a problem with a limited number of alternatives under uncertainty.

Unlike the systems discussed above, ARBORIST is a single objective optimization system. Therefore it is necessary for the decision maker to transform the incommensurable criteria into a unique unit using weighting coefficients to express his preferences.

The Arborist screen is divided into four windows: Function Menu window, Macro window, Focus window and Message window. The user is guided through the whole system by the menus in the Function Menu window.

One of these menus helps the decision maker to build up a decision tree which is then shown in the Focus window. The tree consists of a root node, decision nodes (i.e., nodes with branches which represent alternatives), chance nodes (i.e., nodes at which one outcome of a chance event will occur), end nodes (i.e., the final outcomes that result from the decisions made in conjunction with the chance events) and branches connecting these nodes. An ARBORIST screen showing a decision tree related to our transportation problem is shown in Figure 3.2.

The decision maker can assign descriptions (e.g., PATH1) and values (e.g., COST = 1000) to all nodes and formulas (e.g., $\alpha$ * COST + $\beta$ * PROPERTY_DAMAGE + $\gamma$ * INJURIES)[1] to end nodes.

After these specifications ARBORIST provides the following analysis functions:

- calculate the expected value for the decision tree, and show the "best" solution as a magenta colored path through the tree;
- display the probability distributions for the outcome at a selected chance node as histograms in the Macro window;
- perform sensitivity analysis for one selected parameter at a selected node and display the results in the form of colored curves in the Focus window.

The main disadvantage of ARBORIST is that it is a single objective optimization package and that the user has to prepare all the data for his decision problem himself, i.e., the user always has to input all the data of his problem description in an interactive process, because there are no

1: $\alpha$ , $\beta$ and $\gamma$ in the value specification represent weighting coefficients

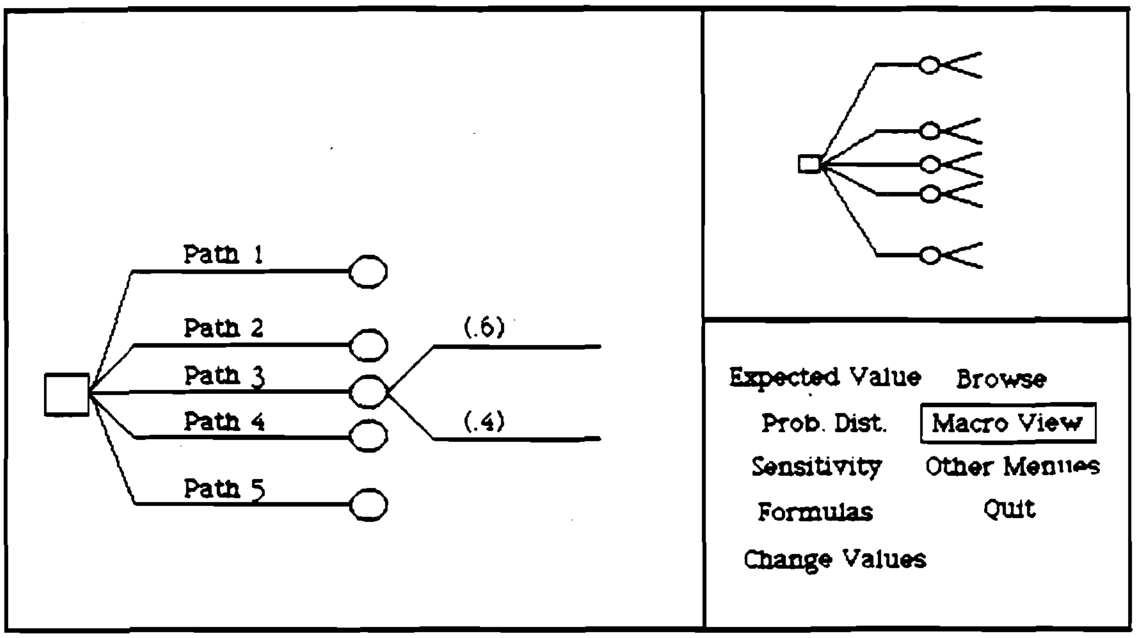



*Figure 3.2: ARBORIST decision tree for sample transportation problem.*

data pre-processors or "hard" computer models in the system.

Despite the disadvantages mentioned, Arborist is a useful tool for decision analysis with uncertainty. Arborist was developed at Texas Instruments Inc. in 1985 and requires a TI-PC or IBM-PC as hardware support.

## 4. THE METHODOLOGY OF MULTI-OBJECTIVE DECISION ANALYSIS*)

The problem mentioned in chapter 2 is a well known discrete, multiobjective decision problem, in which all feasible alternatives are explicitly listed in the finite set $x^0=\{x_1,x_2,\ldots,x_n\}$, and the values of all criteria of each alternative are known and listed in the set $Q=\{f(x_1),f(x_2),\ldots,f(x_n)\}$. There are many tools which could be employed to solve this problem (e.g., Korhonen, 1985, Majchrzak, 1984). We have drawn on the method developed by Majchrzak (1985).

Usually, the procedure of problem solving is divided into two stages. The first stage is the selection of elements of a nondominated set from all the alternatives of set $x^0$. In the second stage, the "best" solution is identified as the decision maker's final solution to the problem under consideration, in accordance with his preferences, experience etc., as the basis for his decision.

In the discrete, multicriteria optimization module of the overall system, at the first stage of problem solving, the dominated approximation method is used to select the elements of the pareto set, because of its calculation efficiency and its ability to solve relatively large scale problems. For instance, this method can be used to solve a problem with 15-20 criteria and more than a thousand alternatives, which is sufficient for processing the data arising from scenario analysis in the framework system.

In the second stage, an interactive procedure based on the reference point theory is employed to help the user to find his final solution. This approach combines the analytical power of the "hard" computer model with the qualitative assessments of the decision maker in the decision process. It makes the decision process more reasonable and closer to the human thinking process. In the following, the methodology used in these two stages will be described briefly.

*) This section is based on the Reference Point Approach developed by Wierzbicki (1979, 1980) and draws on the DISCRET package developed by Majchrzak (1984, 1985).

## 4.1 Selection of the Nondominated Set of Alternatives

### 4.1.1 Problem Formulation

We may describe the problem considered as a minimizing (or maximizing or mixed) problem of m criteria with discrete values of criteria and a finite number of alternatives n.

Let $x^0$ be the set of alternative admissible decisions. For each of the elements of $x^0$, all criteria under consideration have been evaluated. Let Q be the criteria values set for all feasible discrete alternatives in the space of criteria F. Let a mapping $f: x^0 \to Q$ be given.

Then the problem can be formulated as follows:

$$\min f(x) \qquad x \in x^0$$

$$x^0 = \{x_1, x_2, \ldots, x_n\} \subset R^s$$

$$f(x) = \{f^1(x), f^2(x), \ldots, f^m(x)\}$$

$$f: x^0 \to Q$$

$$Q = \{f(x_1), f(x_2), \ldots, f(x_n)\} \subset F = R^m$$

The partial pre-ordering relation in space Q is implied by the positive cone $\Lambda = R_+^m$:

$$f_1, f_2 \in Q \quad f_1 < f_2 \iff f_1 \in f_2 - \Lambda$$

This means $f_1$ dominates $f_2$ in the sense of partial pre-ordering.

Element $f^* \in Q$ is nondominated in the set of feasible elements Q, if it is not dominated by any other feasible element. Let $N = N(Q) \subset Q$ denote the set of all nondominated elements in the criteria space and let $N_x = N(x^0) \subset x^0$ denote the set of the corresponding nondominated alternatives (decisions) in the decision space.

To solve this problem means to delete all the dominated alternatives – that is, alternatives for which a better one can be found in the sense of the natural partial ordering of the criteria – or to find the set N of nondominated elements and the corresponding set $N_x$ of nondominated alternatives. Eventually, a final solution should be found from the set of nondominated alternatives.

4.1.2 The Algorithm to Select the Nondominated Set of Alternatives

The algorithm to select the nondominated set of alternatives is quite simple. The method implemented in our system is of the explicit enumeration type. It is called the method of dominated approximations and is based on the following notion.

**Def. 1:** Set A is called a dominated approximation of N if, and only if

$$N \subset A - \Lambda$$

i.e., if for each $f_i \in N$ there exists $f_j \in A$ such that $f_i < f_j$ in the sense of partial pre-ordering induced by $\Lambda$ .

**Def. 2:** The $A_2$ approximation dominates the $A_1$ approximation of the nondominated set N if, and only if

$$A_1 \subset A_2 + \Lambda$$

The method of dominated approximations generates a sequence of approximations $A_k$, k=0,1,2,...l such that

$$Q = A_0 \supset A_1 \supset \dots \supset A_k \supset \dots \supset A_l = N$$

given Q and $\Lambda$ select N = N (Q), and assuming that all criteria are to be minimized. Then the procedure of problem solving can be described as follows.

**Step 0:** let $A_0 = Q$, $N = \Phi$, $K = 0$

**Step 1:** If $A_k \setminus N = \Phi$ then stop,

else choose any index $i \in I=\{1,2, \dots ,m\}$ and find $f^* \in Q$ such that

$$f^*_i = \min f^i$$

set $N = N \cup \{ f^* \}$ and go to step 2.

**Step 2:** Create the new approximation $A_{k+1}$ by $f^*$

$$A_{k+1} = \{ A_{k+1} \setminus N \} \ \{( f^* + \Lambda ) \cap (A_k \setminus N )\} \cup N$$

set K = K + 1 and go to step 1.

As a result of the above procedure the nondominated set N of alternatives is found when the stopping condition $A_k \setminus N = \Phi$ is satisfied. The selection of the pareto set from all the alternatives in the criteria space is shown in Figure 4.1.

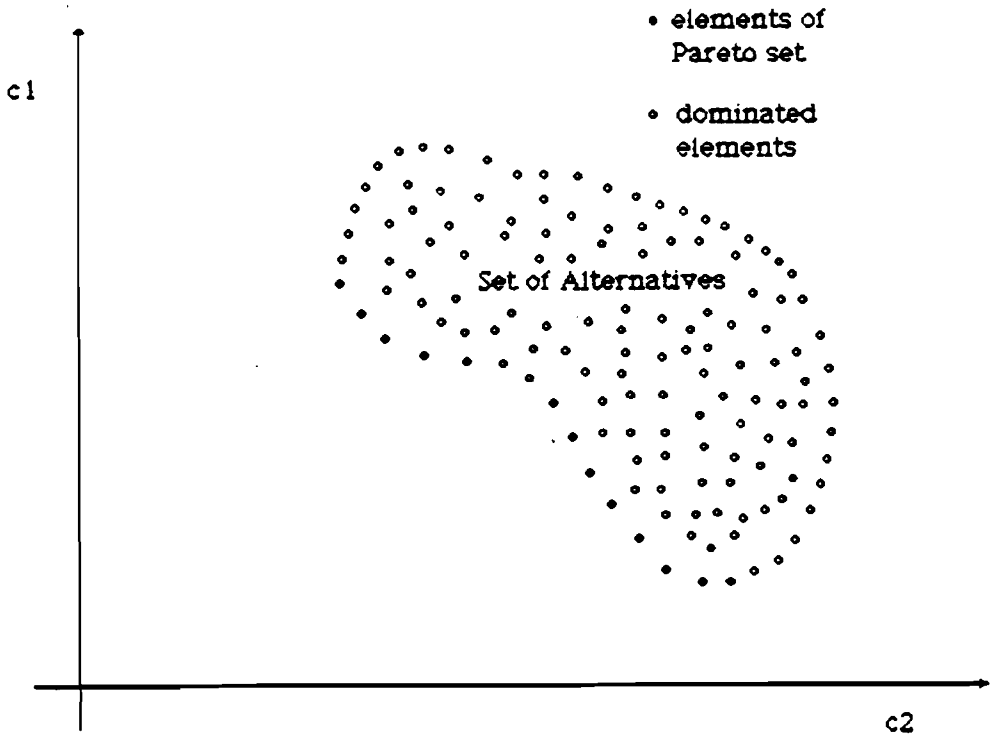



*Figure 4.1: The pareto set from the alternatives in the criteria space*

## 4.2 The Reference Point Approach

### 4.2.1 General Concept

After the system eliminates, by the method mentioned above, all the dominated alternatives, the set of remaining nondominated alternatives is usually large and its elements are incomparable in the sense of natural partial ordering. To choose from among them, additional information must be obtained from the decision maker. The main problem of multicriteria optimization is how and in what form this additional information may be obtained, such that it satisfactorily reflects the decision maker's preferences, experience and other subjective factors.

There are many methods for obtaining that additional information and to then find the final or the "best" solution according to the decision maker's preference. The most common method is the weighting coefficients method, which plays a central role in the basic classical theory of multiobjective decision analysis. It represents a traditional method of multicriteria optimization.

However, certain difficulties often arise when applying the weighting coefficients method to real-world decision processes: Decision makers usually do not know how to specify their preferences in terms of weighting coefficients. Before running a multiobjective model, some of them do not even have an idea about their weighting coefficients.

Most of them are not willing to take part in psychometric experiments in order to learn about their own preferences. Sometimes the decision maker has variable preferences as time, and the information available to him changes. The applicability of the weighting coefficients method to real world problems is severely restricted by these factors.

It is obvious that decision makers need an alternative approach for multicriteria optimization problems. Since 1980 many versions of software tools based on reference point theory have been developed at IIASA, such as DIDASS/N, DIDASS/L, MM, MZ, Micro DIDASS etc. These tools can deal with nonlinear problems, linear problems, dynamic trajectory problems, and committee decision problems. Recently many application experiments have been reported by numerous scientific papers and reports (e.g., Grauer, et al. 1982, Kaden, 1985,).

The reference point approach is based on the hypothesis that in everyday decisions individuals think rather in terms of goals and aspiration levels than in terms of weighting coefficients or maximizing utility. This hypothesis is quite close to the real-world decision-making process.

Using the reference point approach, the decision maker works with a computer interactively. There are two distinct phases in the approach:

In the first stage, the exploratory stage, the decision maker may acquire information about the range and the frequency distribution of the alternatives thus giving him an overview of the problem to be solved. The decision maker may also set some bounds for the criteria values of the alternatives set to focus his interests on a certain area.

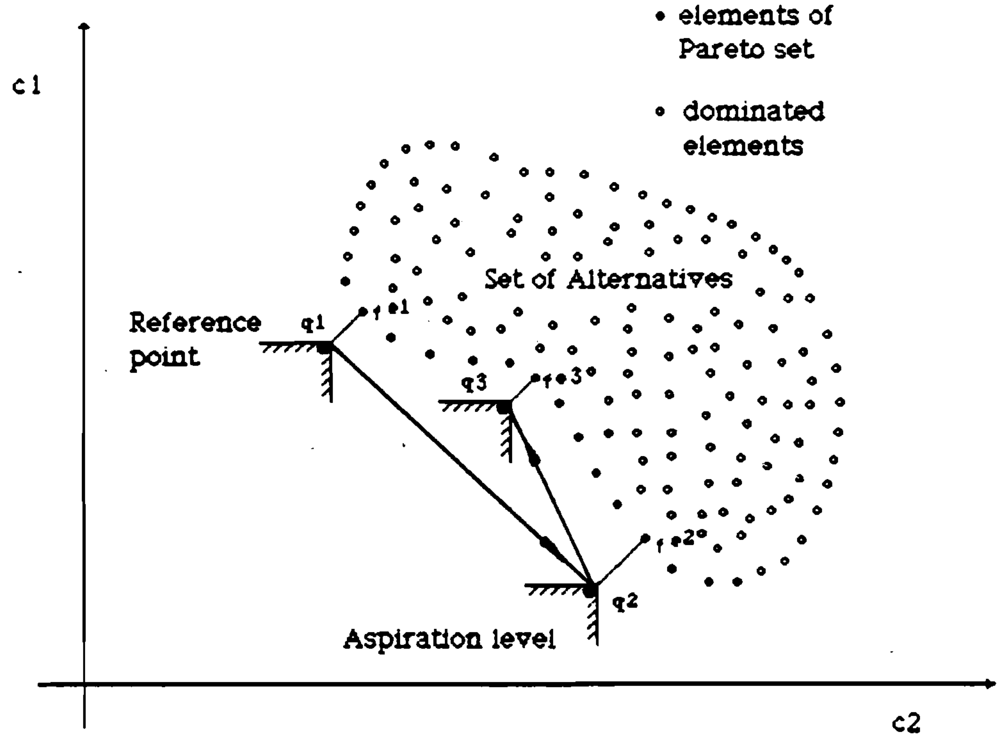
In the second stage, the search stage, at first the decision maker is required to specify his preferences in terms of a reference point in the criteria space. The values of the criteria represented by the reference point in the criteria space are the values the decision maker wants to obtain, i.e., the goal of the decision maker, which reflects his experience and preferences.

Next, the system identifies an efficient point, which is one of the alternatives closest to the reference point. The efficient point is the "best" solution of the problem under the constraints of the model and with respect to the reference point specified by the decision maker.

If the decision maker is satisfied by this solution, he can take it as a basis for his final decision. If the decision maker is not satisfied by this solution, he may modify his goal, i.e., change the reference point or change the constraints, i.e., change the bounds he had set before, or both, or create some additional alternatives in order to obtain a new efficient point. In the case of continuous variables problems, i.e., the problems described by continuous models (linear or nonlinear programming models or dynamic control models), the reference point method is able to generate new alternatives by running the model again.

### 4.2.2 The Mathematical Description of the Approach

The approach currently implemented in the framework system is as follows: for the sake of computability, it is necessary to define an achievement scalarizing function which transforms the multiobjective optimization problem into a single objective optimization problem. After having specified his preferences in terms of a reference point, which need not be attainable, the decision maker obtains an efficient point which is the nondominated point nearest to the reference point in the sense of the scalarizing function.




*Figur^ 4.2: The interactive procedure of the reference point approach*

In our data post-processor the Euclidean-norm scalarizing function is used. Let q be the reference point specified by the user. Then assuming that the optimization problem under consideration is a minimization problem for all criteria (for maximizing problems one may easily transform it into a minimizing problem by changing the sign of the related criteria), the following scalarizing function is minimized:

$$S(f-q) = -\,||(f-q)||^2 + \rho\,||(f-q)_+||^2$$

where $(f-q)_+$ denotes the vector with components max(0,f-q), ||.|| denotes the Euclidean norm and $\rho$ >1 is a penalty scalarizing coefficient.

The solution $f^e$ for minimizing the scalarizing function S is an efficient point of the problem with respect to the specified reference point.

If necessary, this procedure can be repeated until the decision maker is satisfied by an efficient point.

Figure 4.2 shows that after changing the reference point twice, finally the decision maker obtains a satisfactory efficient point $f^{e3}$ corresponding to reference point $q^3$.

## 5. IMPLEMENTATION

In the overall software system, the multi-criteria optimizer or post-processor is implemented as an independent module as well as an optional function of several other modules, notably the transportation risk-cost analysis model. The only difference is in terms of access – either from the system's master menu level, or from the appropriate level of other models. If used as a stand-alone module, the program first examines its data directory and lists all data sets by a one-line identification in a sequence depending on modification dates, i.e., the data set generated last is offered as the first choice. The user then simply points at the desired data set, which is then loaded for further analysis.

Wherever the multi-criteria optimization package is used as an intergrated post-processor, this step is not necessary, since only one data set, namely the one generated with the current model, will be examined.

In case of the transportation risk-cost analysis model, this data set, one record for each feasible alternative generated, consists of:

- an alternative identification;
- an array of criteria for each feasible transportation alternative;
- additional model output for each alternative, e.g., the node-arc sequence of the path;

- an array of control and policy variables corresponding to each alternative.

All interaction with the system is menu-driven. At the top level, summary information on the set of alternatives loaded is provided (Figure 5.1).

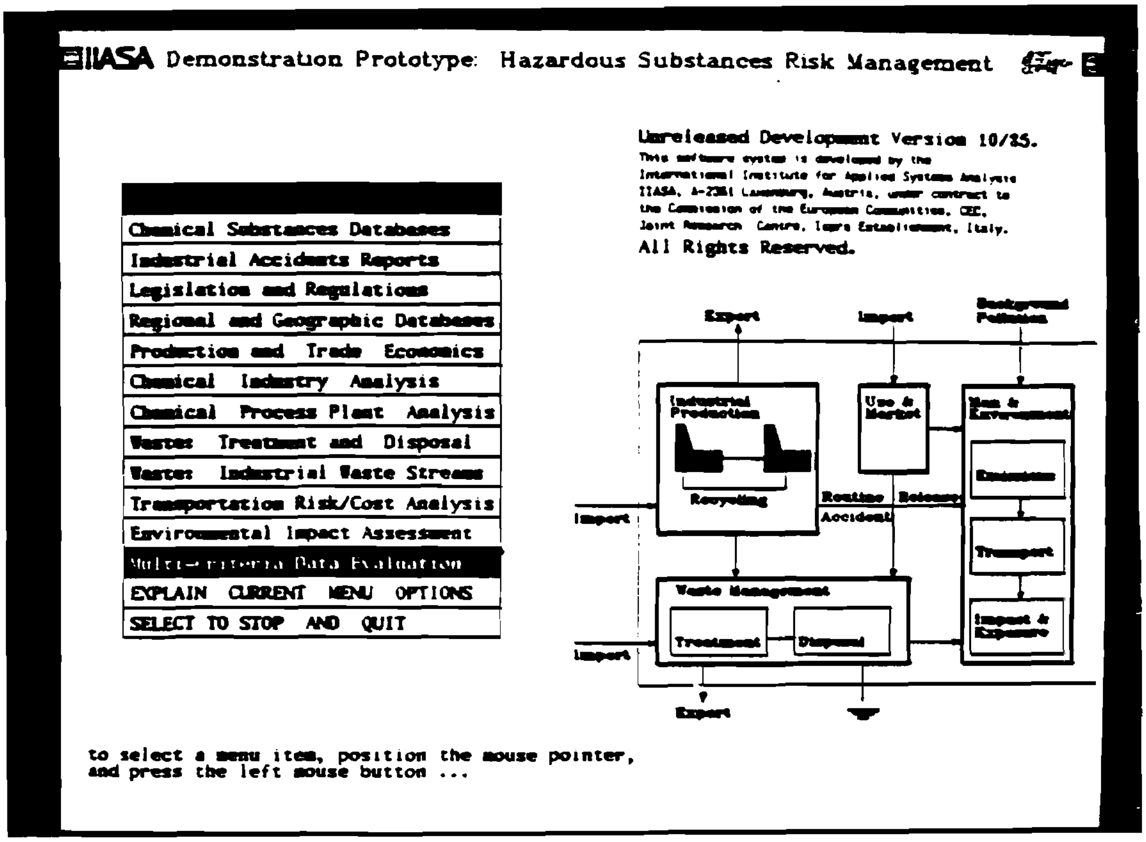



*Figure 5.1a: Top level menu: selection of the post-processor*

This information includes:

- the number of alternatives;
- the number of criteria considered;
- a listing of criteria, together with their status information (default settings for the three possible status indicators ***minimize***, ***maximize***, ***ignore***), and basic statistical information (average, minimum, maximum) for the individual criteria.

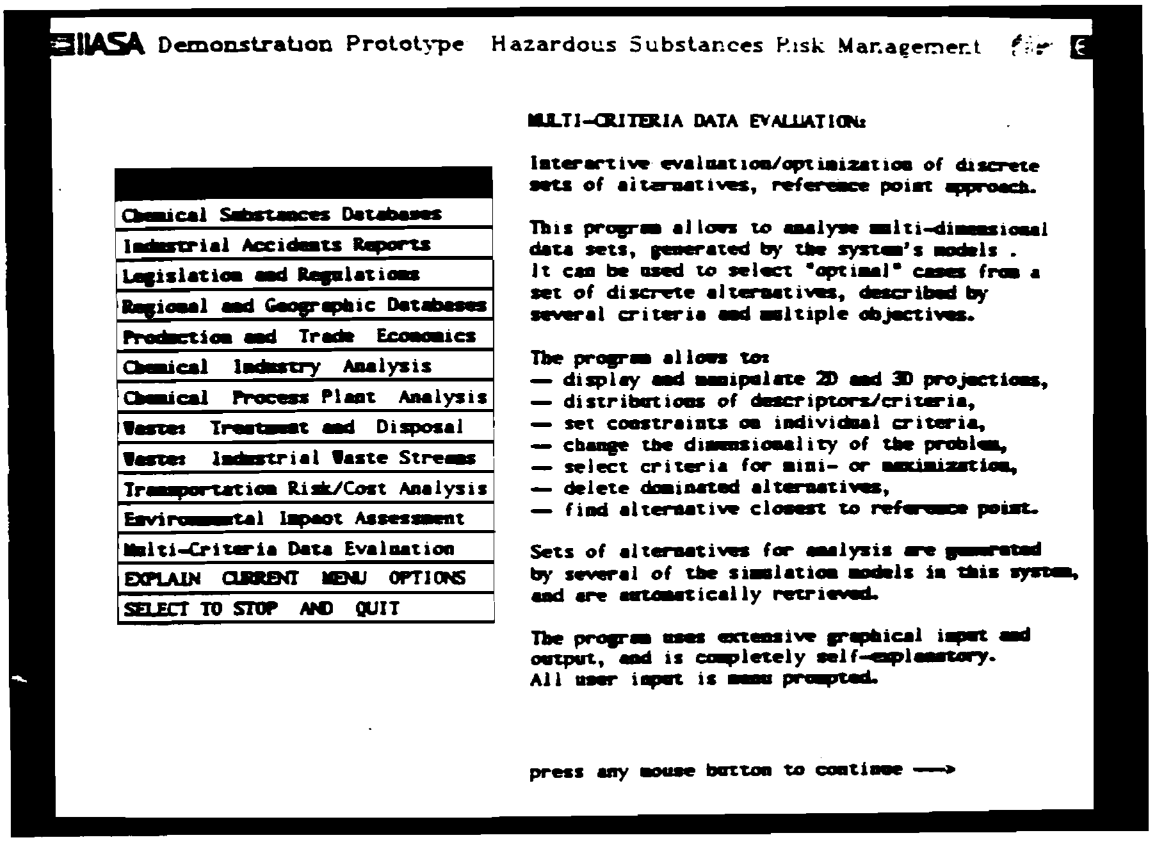



*Figure 5.1b: Top level menu: explain current menu option*

At that level, the menu offers the following choices:

- *display data sets available for analysis:* (Figure 5.2);
- *select criteria:* this allows the user to modify the status characterization, i.e., change the dimensionality of the problem by ignoring or including additional criteria from the list (Figure 5.3);
- *statistical analysis*: here statistical information on the data set other than the minima, maxima, and average values displayed by default can be generated and displayed. In particular, this includes standard deviations and median values as well as pairwise and multiple correlation coefficients, indicating relationships of indicators. Also, a cluster analysis option is foreseen, allowing a similarity ranking of alternatives and subsets of alternatives.

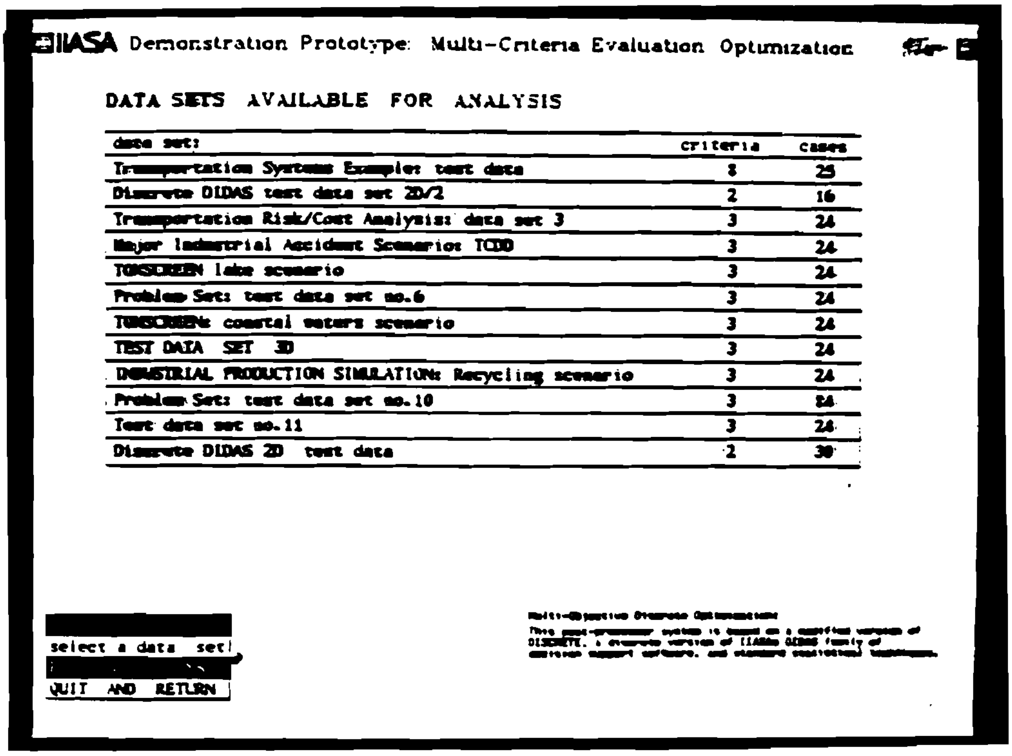



*Figure 5.2: Selection of data set*

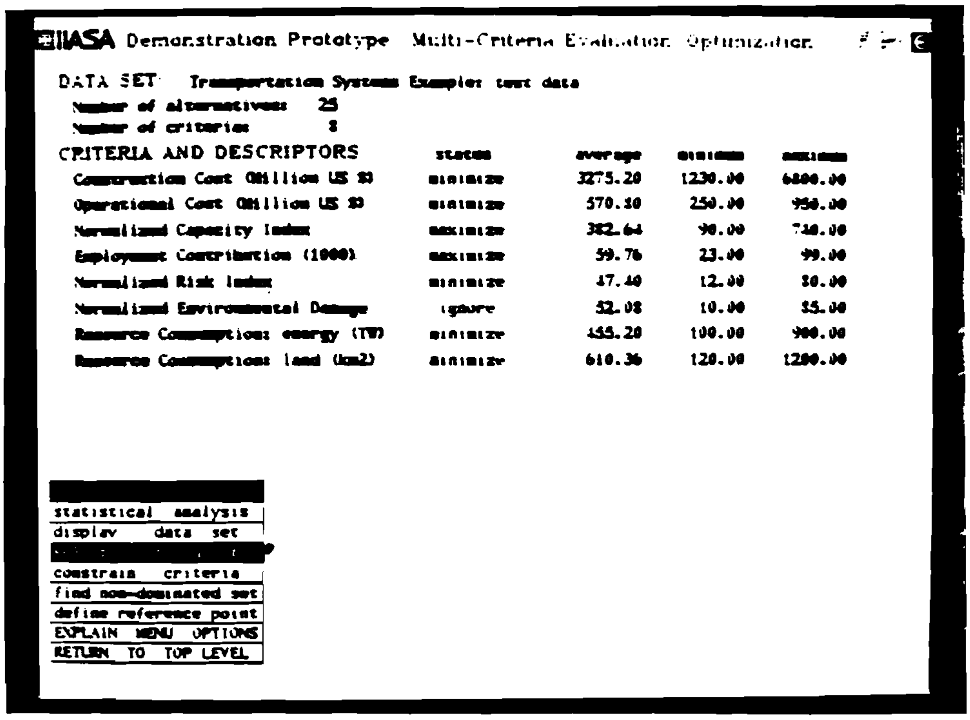



*Figure 5.3: Basic information on criteria/selecting set of criteria*

- *ranking by individual criteria:* here the alternatives are ranked according to the individual criteria, resulting in a table of color-coded relationships.
- *display data set:* this invokes the second level menu for the display options, discussed below;
- *constrain criteria:* here upper and lower bounds for the individual criteria can be defined, based on a graphical representation of the range and distribution of the criteria values (Figures 5.3 and 5.4); setting these constraints results in the reduction of the set of alternatives considered; the bounds are defined by dragging, with the mouse graphical input device, a vertical bar within the range of criteria values, and cutting off alternatives left or right of the bar. The system displays the current value of the constraint, and indicates how many alternatives will be deleted whenever the user sets a constraint. If the constraint setting is verified by the user, the alternatives excluded are deleted from the data set and new values for the descriptive statistics are computed.
- *find pareto set:* this option identifies the set of nondominated alternatives (see section 4.1), and indicates how many nondominated alternatives have been identified;
- another feature at this, as well as any other, level in the system is an explain function that provides a more detailed explanation of the menu options currently available.

The option: *display data set* generates a new menu of options. The display options are:

- *default scattergrams:* the default scattergrams provide 2D projections of the data set, using pairwise combinations of the relevant criteria (Figure 5.5). The first three combinations are displayed in three graphics windows. If the set of nondominated alternatives has already been identified, the pareto-optimal points will be displayed in yellow and will be larger than the small, red, normal (dominated) alternatives;

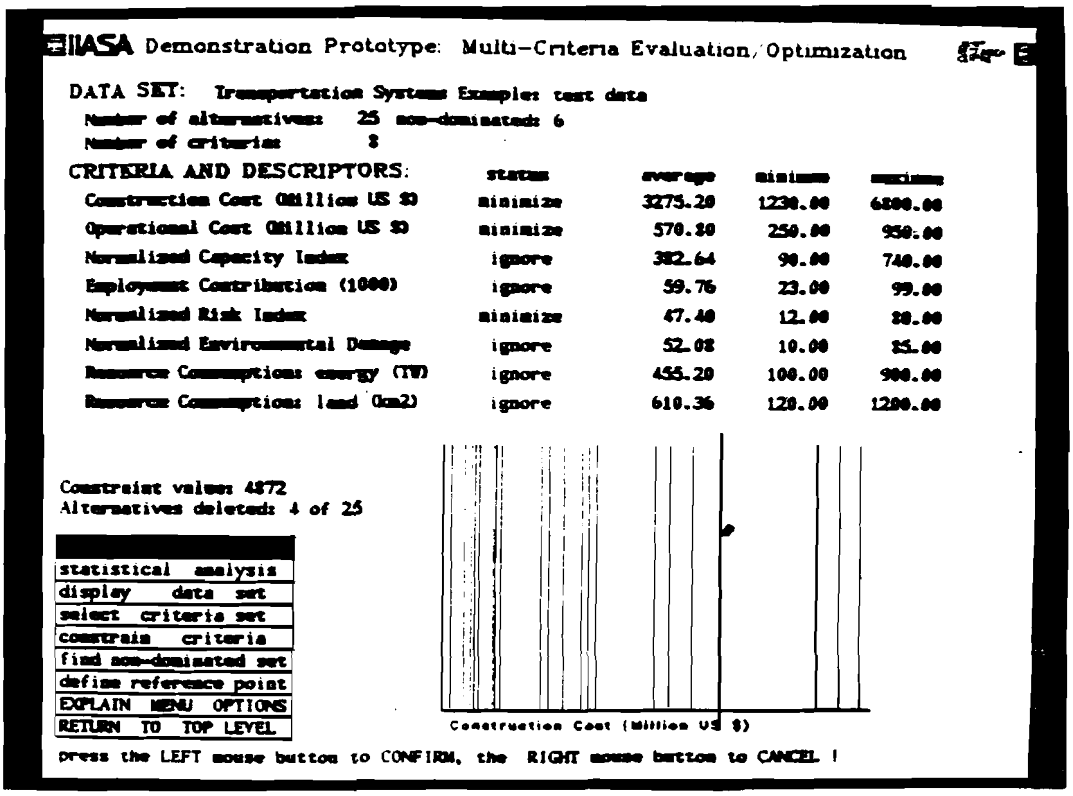



*Figure 5.4: Setting constraints on criteria*

- *default distributions:* this option displays the first three relevant criteria as discretized frequency distributions (Figure 5.6); again, three criteria distributions can be displayed simultaneously;
- *display selection, select x-axis, select y-axis:* these three options are used to display criteria combinations other than the default selections. Defining the x-axis only, by identifying one of the criteria lines by pointing at it, and then selecting one of the graphics windows for display, a frequency distribution will be displayed; if x and y axis are identified, a scattergram will be produced. Thus, any combination of distributions and scattergrams can be generated (Figures 5.5 and 5.6), allowing the user to gain some insight into the geometry and structure, e.g., dependencies of criteria, of the data set. Also, on the basis of the graphical display, it is much easier to define constraints (by returning

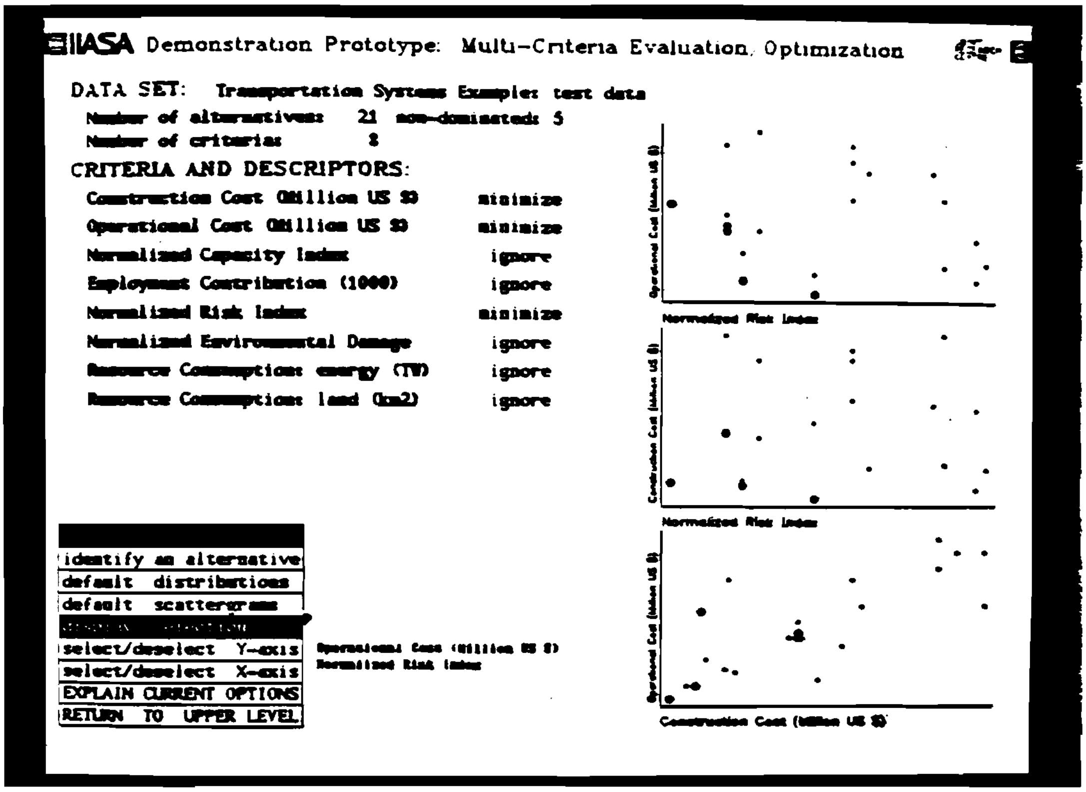



*Figure 5.5: Data display: scattergrams*

to the previous level and invoking the appropriate menu option), if solutions are obviously clustered, i.e., distributions are multi-modal.

- *identify alternative:* one individual alternative can be identified by pointing at one of the dots in either of the graphics windows. The dot will be marked by a large blue dot in all the scattergrams currently on display. Repeating this identification process several times, changes in the relative position of these identifiers along the individual axes support some intuitive impression on trade-offs among criteria. Parallel to marking the selected alternative on the scattergrams, numerical values for the individual criteria are displayed (Figure 5.7).

The most powerful option in this system, however, is the selection of a reference point and the resulting identification of an efficient point (see section 4.2).

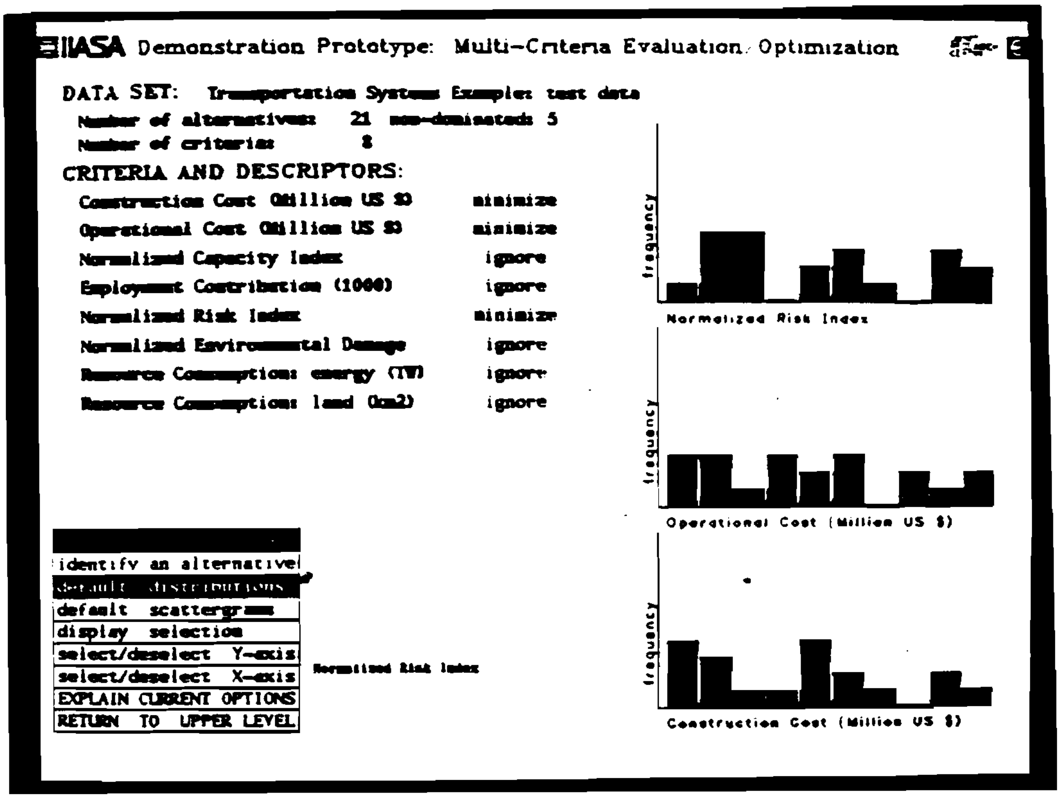



*Figure 5.6: Data display: frequency distributions*

Depending on the level at which a reference point is defined, two techniques for its identification are supported, namely a numerically oriented one, considering all criteria simultaneously, and a graphically oriented one based on a sequence of pairwise trade-off specifications (Figure 5.8).

In the first case, the (extended) range for each of the criteria is displayed besides the listing of the criteria. Thus, while all criteria as well as the utopia points and the possible ranges for a reference point are in view, the user can specify the desired level (aspiration level) for each or a few of the criteria by selecting the respective criterion and then entering either a number or pointing at an appropriate position within the interval displayed (Figure 5.8). For the dimensions (i.e., criteria) not explicitly specified by the user, the reference point value defaults to the utopia point's value.

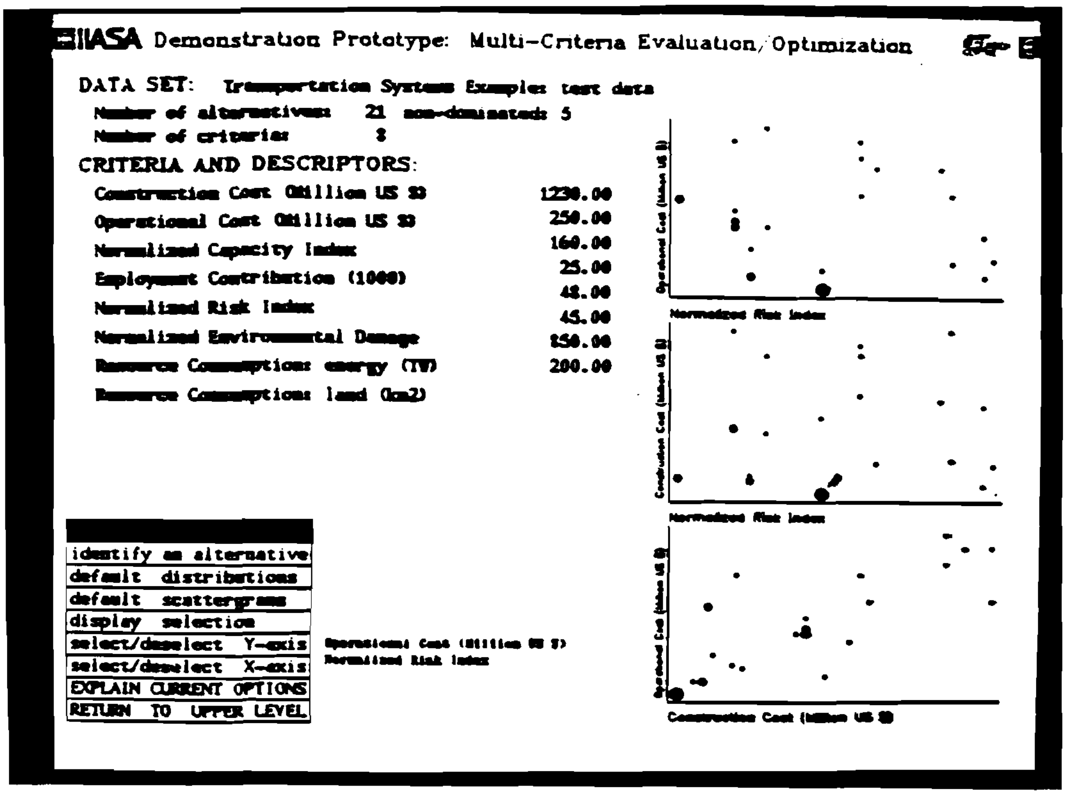



*Figure 5.7: Identifying and cross-referencing alternatives*

In the second case, the user can have up to six scattergrams on the screen (covering up to a total of twelve criteria simultaneously). For each pairwise combination of criteria, he can then specify a reference point in this 2D projection, thus defining two dimensions at a time. Since the same dimension can be displayed in more than one scattergram, more than one value could be specified for any one dimension. Therefore, as soon as a value for a dimension that is represented more than once is set, a vertical or horizontal line, indicating this setting, is displayed in all other scattergrams with this dimension. This serves as a reminder to the user that this dimension was already defined. If the user sets another value for this dimension anyway, all previous settings are updated accordingly, since the last specification always supercedes any previous one.

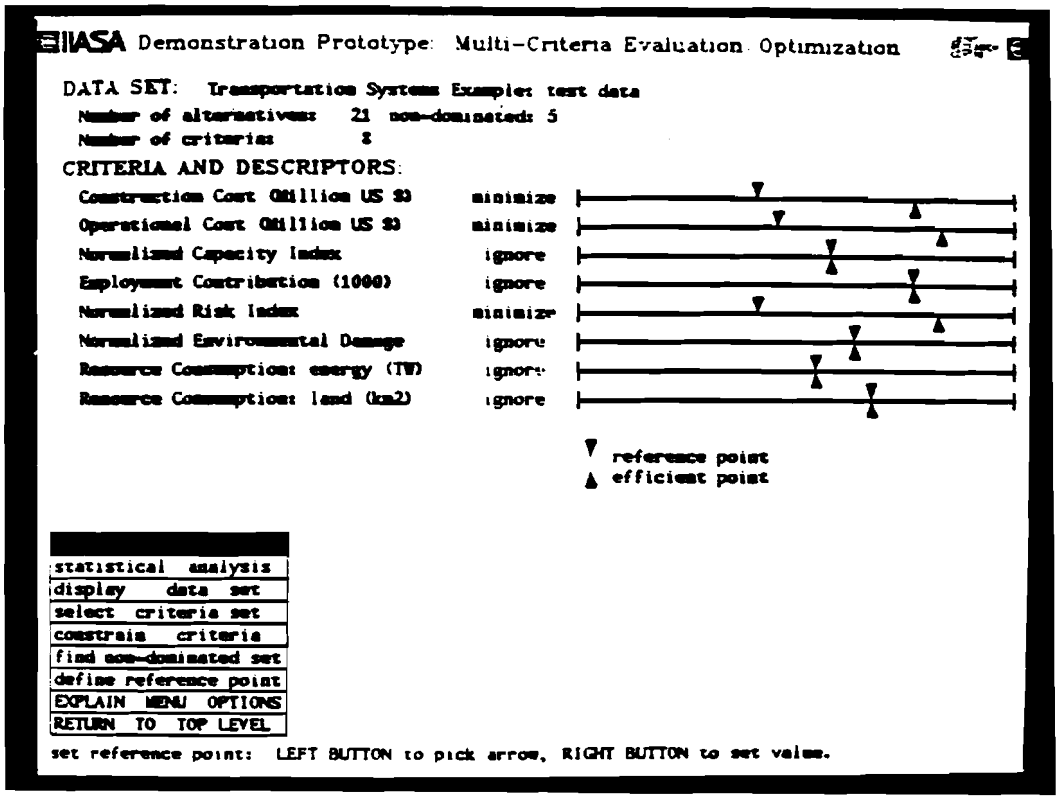



*Figure 5.8: Defining a reference point with criteria list*

Once all or a subset of the criteria dimensions deemed important by the user have been defined, this reference point will then be used to find an efficient point as the solution to the selection procedure (see section 4.2). Several rounds of iteration, however, may be used to find a satisfying solution. With each efficient point, the user has the option of returning to the model that generated the alternative selected (Figure 5.9). There he can re-simulate the alternative, and thereby generate additional descriptive information on his choice. This may lead to yet another setting for the reference point, another efficient point and so on.

Another possible course of action is in investigating the robustness and sensitivity of the solution. Robustness can be tested at the DSS level: here the system successively increases a noise term added to the raw data, until the efficient point, as defined by the current reference point, switches to

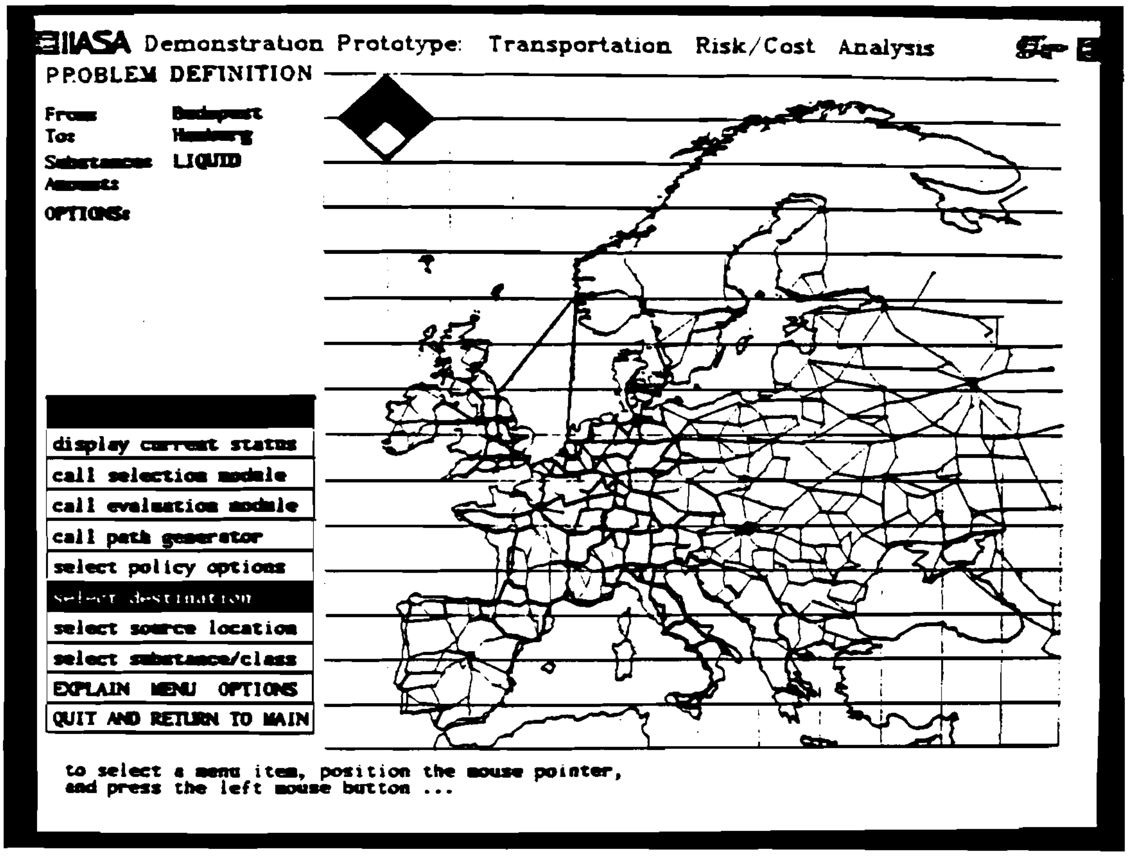



*Figure 5.9: Display of a preferred solution at the level of the original model.*

another alternative. The noise level, (in percentage) is then displayed to the user. The indication is that with an assumed error of the model output up to the level indicated, the solution would stay the same, not be affected, i.e., robust. The higher the noise level indicated, the more confidence may be placed in the selection of the alternative.

Sensitivity analysis, on the other hand, could be performed by switching back to the original model and exploring the neighborhood of the preferred solution. Small changes in critical control variables and parameters should not result in drastically different model outcomes, that, if reintroduced into the DSS system, would be dominated and far from the efficient solution.

In summary, the discrete optimizer or post-processor is a tightly coupled option of several simulation models used for scenario analysis and/or generating a larger set of alternatives to be evaluated. Providing a combination of analysis and display options, powerful decision support can be made available to a non-expert user in a very efficient and effective way. Due to the ease of use, the high degree of flexibility and responsiveness, and the immediate understanding of results based on symbolic and graphical display combined with numerical information, the system invites a more experimental style of use. Complex models, which usually produces a confounding amount of output, can thus be made available as a direct information basis for decision making.

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