Computer Science Journal of Moldova, vol.4, no.2(11), 1996

Working Out R&D Programs via Multicriteria Analysis

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Abstract

This paper describes the development of a decision support system, which was worked out to analyse and to select Research and Development (R&D) projects. A brief survey of R&D project selection methodologies and aspects is given. The described DSS was constructed round the approach, where ranking is used to generate numerical values for each project. Then the problem of R&D project selection becomes a knapsack problem. Its specific aspect depends on the financing policy selected by the decision maker. A final section provides an overview of some practical implementations of multicriterial decision aids made by OR Group of Institute of Mathematics of Moldavian Academy of Sciences.

1 Introduction

In public decision making there is no exhaustive single criterion. That is why one has to deal with a number of quantitative as well as qualitative criteria in order to make an appropriate selection. In such a context, multicriteria analysis methodologies, widely involving the decision maker – analyst (computer) relations, are well–suited to solve the decision making problems.

The evolution of the decision maker – analyst relations is sufficiently sensitive in multicriteria analysis. This kind of relation can be realized using two distinct classical approaches. The first one applies methods based on the attractive idea to include the decision maker as an active element of the decision aid process. This interactive method can be presented as an iterative procedure which alternates two kinds of phases:

- calculation phases (executed by an analyst or a computer);
- dialogue phases, involving the decision maker.

Each procedure iteration presents the decision maker a proposal which consists of one ore several alternatives against which the decision maker reacts and provides some preference information. This information is then used to construct (calculate) a new proposal. The cycle continues until an appropriate proposal is obtained. The wide succes met by this approach can be illustrated by a large number of surveys, studies and applications ([3]–[6]).

Unlike the first (interactive) approach, the second one aims at defining a synthetic and definite aggregation rule based in the decision maker's preference structure. Such a rule can be defined using multiattribute utility theory (through an analytic formulation) (e.g. [1], [2]) or via outranking methods (using binary preference relations) ([7]–[11]). This rule is then applied to the set of alternatives in order to get the final prescriptions.

Both the mentioned approaches (as well as some mixed variants of them) are widely exploated to solve different kinds of multiple criteria decision problems. The R&D project selection problem described in this paper arose out of requirements to develop a year work program of a unit (of economical nature, financial or other), specified in terms of individual proposed research and development projects. As a rule, project proposals in any one year tend to exceed the available resources by a considerable amount, so that an important part of them have to be rejected (dropped). In order to decide which of the presented projects are to be included in the portfolio for the year, a number of conflicting criteria, reflecting economical, technical, personnel development and other type of goals, have to be taken into account. Thus the problem has to be seen as a typical multicriteria decision making problem.

The R&D project selection problem has been widely considered in the literature. So, [12] gives a review of R&D project selection methodologies and multicriteria aspects of the problem. It should be noted, that the most of described approaches do not make use of modern multicriteria decision making methods, relying more on other types of analysis and structured aids.

In [13] the R&D project selection problem is formally set in an multiple criteria decision making framework. The approach described here is based on the procedure of identifying an underlying utility function. In a somewhat different but related context in [14] the goal programming coupled to a Delphi process is used to identify the utility function. It is necessary to mention that both of these approaches require considerable efforts to generate judgemental inputs, allowing a lot of questions of "what if" type. The problems of the formal use of multi-atribute utility functions for R&D project selection problems have also been discussed in [15] and [16], where is concluded, that the corresponding approach is feasible in a right context only.

A somewhat different approach is suggested in [17], where the R&D project selection problem is treated as a classic operational research problem: if a clearly defined value can be associated with each potential project then the corresponding problem becomes effectively a knapsack problem. The implementation of this approach is discussed in the next sections. A related approach with the previous one is given in [18], where subjective ranking is used to generate pseudo-values for each project, but this seems to be most appropriate in the situations with relatively small numbers of projects (since individuals are required to rank order projects directly).

A rather different approach is the reference point approach, suggested in [19] and discussed further in [20]. This approach is based on the concept of a reference level, i.e. a set of a performance measures for each attribute representing (in some sense) a realistically assessed desired level of achievement for each attribute. The basic principle here is to find for the corresponding optimization problem the closest feasible and non-dominated solution to the point defined by reference levels. The reference point approach, presented in a suitable form for R&D project portfolio selection problem, was succesefully used in [21].

As long as the list of projects represents a multiattributed consequence and the problem of project selection is often characterized by a very large number of possible portfolios, an interactive decision support system to assist in the selection of an appropriate project portfolio would be very useful.

The proposed system was designed to provide the following functions and information:

- user editing of available resources, list of criteria (including their scales and relative importance), evaluation of projects and policy of financing. These facilities allow the user to perform any desired "what if" evaluation;
- fixing of certain projects either in or out of the program, so that they will not be considered during the selection of a portfolio variant;
- providing with the information pertaining to the submitted projects and current variant of portfolio (obtained as a result of an optimization process) at any work phase;
- provision for the user (decision maker) to switch projects in or out of the current portfolio: the system updates the output and warns of any financial resources overruns;
- reoptimization under new conditions. In that way the decision maker is able to get more variants of program portfolio;
- saving the obtained results for later re-evaluation and analysis.

Within the framework of the DSS scheme, described in this paper, the processing of the information concerning submitted projects and selection of the plan of their financing consists of the following two stages:

I. Multicriteria analysis made on the whole set of projects;

II. Selection of a subset of the projects (variant of the financing plan) in accordance with the policy of financing determined by the decision maker.

Before discussing these two stages we shall first outline the initial data to be provided within the proposed portfolio selection DSS.

2 Initial Data

A preliminary expert analysis of all the projects, submitted for financing within the framework of a particular program is supposed to be done. A list of M criteria is defined in order to evaluate every project from a finite set of N projects. Each criterion is an application from the set of projects to an ordered (numerical or non-numerical) set. The list of criteria has to be fully adequate as a set of operational attributes for decision analysis including urgency of project, value to client if successful, probability of success in project, technical resources for project completion and so on.

Thus, the initial data, relating to submitted projects, include the information concerning directly the projects, as well as the information obtained as a result of an expert evaluation of the projects under the defined criteria. Besides, the initial data contain also data concerning criteria and restrictions for project selection.

The general structure of initial data can be represented as follows:

1. the data relating to each criterion j from the set of criteria $J = \{1, 2, \dots, M\}$:
    - the name of criterion;
    - type, numerical or non-numerical (in the last case the ordinal scale of the criterion is also given);
    - objectiv (maximization or minimization);
    - weight of the criterion π_j (non-negative), used as a mesure of the relative importance of the corresponding criterion. All the weights have to be taken equal if the criteria have the same importance for the decision maker.

2. data concerning the submitted projects:

- initial data on each project $i \in I = \{1, 2, \ldots, N\}$ including name, its cost c_i and term of fulfilment t_i, etc.
- data, resulting from expert analysis of project i, i.e. expert evaluations $e_{ij} \quad (j = 1, 2, ..., M)$, where e_{ij} is the evaluation of the project i under criterion j;

3. restrictions for selection of the financing plan of the projects:
   - available financial resources C;
   - subset of the projects, which should be included in the plan of financing;
   - subset of the projects, which should be excluded from the plan of financing;
   - policy of financing.

Additional initial information may be necessary to allow for the possibility of certain projects either being mutualy exclusive from the portfolio because they represent alternatives on the same essential problem, or being included together, as far as they favour the solution of sertain global problems. For ease of presentation, the information concerning such kind of possible relations between projects is not included into the initial data explicitly and is disscused in the next sections.

In order to define a financing policy, the following possible alternatives are assumed:

- partial financing of the projects is allowed;
- financing of the projects proportionally to their costs or to multicriteria indexes of preference — values of the project;
- consideration of the relations between the projects,

and other.

Before going on to the next point, we shall first outline some specifications and functions which were taken into account, when the portfolio selection DSS was worked out. Namely, the following minimum requirements for the functioning of the DSS were considered:

- the DSS should be capable of generating information concerning projects comparison, i.e. preference structures on the set of submitted projects. This kind of information was found to be very useful while selecting an appropriate project portfolio;

- the system should be capable of generating "good" feasible solutions to the portfolio selection problem, but should also allow the user to override the system recommendation easily, i.e. to insert projects in portfolio or to delete them;

- the system must generate the "best" solution in some sense, even if this solution may be modified at a later stage;

- the user must be able to perform operatively a variety of "what-if" scenario evaluations, by seeing the effect of changing criteria importances, fixing certain projects into or out of the portfolio, revising financing policy.

All the above features may well occur in any other project selection problems, even if they arose directly from a specific problem statement.

3 Multicriteria Analysis

Within the framework of this stage a clearly defined numerical multicriteria index of preference v_i, called further as the value of the project, is associated with each submitted project i from the set $I = \{1, 2, \dots, N\}$. The calculated index reflects the relative "quality" of the corresponding project under the whole set of criteria. To get the values of these indexes the approach proposed in [11] (briefly described below) was used.

The method of calculation of the project value is based on the application of preference function $P : I \times I \to [0, 1]$, describing intensity with which an alternative is preferred to other one:

$P(i_1, i_2) = 0$	—	means indifference between the actions i_1 and i_2;
$P(i_1, i_2) \sim 0$	—	means weak preference of i_1 over i_2;
$P(i_1, i_2) \sim 1$	—	means strong preference of i_1 over i_2;
$P(i_1, i_2) = 1$	—	means strict preference of i_1 over i_2.

This function is implemented as a function of difference of evaluations of alternatives on each separately taken criterion:

$$P(i_1, i_2) = H(d),$$

where $d = max\{0, e_{i_1 j} - e_{i_2 j}\}$ and $H(\cdot)$ is a non–decreasing function defined on $[0, +\infty)$ (the so called generalized criterion) with the property $H(0) = 0$.

The generalized Gaussian criterion (e.g. [11]) was used to generate the preference intensities:

$$H(d) = 1 - exp\,(-d^2/2\sigma^2),$$

where the determination of σ is easily made according to the experience obtained with the Normal distribution in statistics. This kind of the generalized criteria has no discontinuities and guarantees stability of the results.

Next, if $\pi_j \quad (j \in J)$ denotes the defined weights of the problem criteria then one can easily get the normalized weights ω_j, $\sum_{j \in J} \omega_j = 1$, where

$$\omega_j = \frac{\pi_j}{\sum_{l \in J} \pi_l}.$$

Now, the multicriteria preference index ν, representing the intensity of preference of action i_1 over action i_2, when considering simultaneously all the criteria, is defined as the weighted average of the preference functions values:

$$\nu(i_1, i_2) = \sum_{j \in M} \omega_j P_j(i_1, i_2).$$

Obviously, $0 \leq \nu(i_1, i_2) \leq 1$, and

$\nu(i_1, i_2) \sim 0$ — means weak preference of i_1 over i_2 under all the criteria;

$\nu(i_1, i_2) \sim 1$ — means strong preference of i_1 over i_2 under all the criteria.

The total intensity with which the alternative i_1 prevails over all the other alternatives is now found as

$$\varphi^+(i_1) = \sum_{i \in I} \nu(i_1, i),$$

while the total intensity, with which all the other alternatives from I predominate over the alternative i_1 is expressed by

$$\varphi^-(i_1) = \sum_{i \in I} \nu(i, i_1).$$

Further, the net intensity of preference, corresponding to action i_1 is defined by

$$v_{i_1} = \varphi(i_1) = \varphi^+(i_1) - \varphi^-(i_1).$$

One can easely notice that the value of this parameter for any arbitrary alternative i may be positive, as well as negative:

$$1 - N \leq v_i \leq N - 1.$$

The inequality $v_i > 0$ specifies the fact, that the alternative i predominates the other alternatives from I in a greater degree than it is predominated by them, while the inverse inequality reflects an opposite effect.

The determined set of values of the considered projects allows to construct on the set I a preference structure of the type (P', I'). In other words, for any pair of projects $(i_1, i_2) \in I \times I$ one of the following relations is valid:

$$\begin{cases} i_1(P')i_2, & \text{if } v_{i_1} > v_{i_2} \text{ — project } i_1 \text{ outranks project } i_2; \\ i_1(I')i_2, & \text{if } v_{i_1} = v_{i_2} \text{ — project } i_1 \text{ is indifferent to project } i_2. \end{cases}$$

Thus, this kind of a preference structure induces a complete preorder on the set of projects.

Although it is easier for the decision maker to solve some decision problems by using the complete preorder only, a partial preorder on the set of actions would contain more realistic information that can be very useful for the decision making. In this context, for each pair of the projects (i_1, i_2) the following pair of relations is defined:

$$\begin{cases} i_1(P^+)i_2, & \text{if } \varphi^+(i_1) > \varphi^+(i_2); \\ i_1(I^+)i_2, & \text{if } \varphi^+(i_1) = \varphi^+(i_2) \end{cases}$$

and

$$\begin{cases} i_1(P^-)i_2, & \text{if } \varphi^-(i_1) < \varphi^-(i_2); \\ i_1(I^-)i_2, & \text{if } \varphi^-(i_1) = \varphi^-(i_2) \end{cases}$$

The final partial preorder $(P", I", R")$ is then a simple intersection of two preorders induced by this pair of relations:

$$\begin{array}{llll} i_1(P")i_2, & \text{if} & i_1(P^+)i_2 & \text{and} \;\; i_1(P^-)i_2 \\ & \text{or} & i_1(P^+)i_2 & \text{and} \;\; i_1(I^-)i_2 \\ & \text{or} & i_1(I^+)i_2 & \text{and} \;\; i_1(P^-)i_2; \\ i_1(I")i_2, & \text{if} & i_1(I^+)i_2 & \text{and} \;\; i_1(I^-)i_2; \\ i_1(R")i_2 & \text{otherwise.} & & \end{array}$$

The output data of the multicriteria analysis include the information wich describes the preference structures generated on the set of proposed projects:

- total preference preorder;
- partial preference preorder,

and preference indexes (values) of all the projects.

The described approach to this stage does not require too many information on the decision maker's attitude and is characterized by a remarkable simplicity in its conceptual structure and in the analytical procedure itself. However, this approach still has the main disadvantage of outranking methods, consisting in the lack of a quantitative differentiation of ranked actions. This disadvantage could limit in many cases its aplication. We are also fully aware of the very difficult problem of fixing the weights for the criteria. The necessity in determination of a such kind of values can be considered as another disadvantage of the described approach.

4 Project Selection

The stage consisting in working out the projects' financing reduces to optimization problems, determined pursuant to the policy of financing, selected by the decision maker.

Within the framework of the current stage it is supposed, that two types of the relations between two or more projects can be defined on the set of projects. The first type of the relations is defined by groups involving the projects, having identical (or very similar) purposes, concerning the same economic or technical problems and so on. It is natural to qualify such kind of relations as the relations of competition. When a policy of financing takes into account relations of competition, only one of the projects of a separate group (namely, the "best" one) can be included in the plan of financing. The only exception is the case, when the decision maker includes himself any of these projects in the plan. One can define up to $E(N/2)$ such groups of projects, where $E(\alpha)$ denotes the integer part of number α. Any of the projects may belong to not more than one group of competitors. Thus, if $I_l^c \quad (l = 1, \dots, n_c)$ designate n_c of such groups, $I_l^c \bigcap I_k^c = \emptyset$ for any pair of different indexes $l, k \in \{1, \dots, n_c\}$.

The second type of the relations corresponds to the relations, named conditionally as complement relations and are determined by groups of projects, which being accepted together promote achievement of more global purposes, solve more general problems and so on. In this case the decision maker is the unique decisive factor in determing which groups are to be included completely in the plan of financing, and which are not. As well as in the case of competition relations, any project can be included only in one group of complement. Thus, $I_l^a \bigcap I_k^a = \emptyset$ for any $l, k \in \{1, \dots, n_a\}, \quad l \neq k$, where $I_l^a \quad (l = 1, \dots, n_a)$ are groups of the specified relations and n_a is their number.

The decision maker is able to define a subset of projects, which will be excluded from the set of projects being analysed in order to generate a project portfolio, as well as a subset of projects which will be already included in portfolio on the pre–selective stage. If I_- and I_+ denotes respectively the two defined subsets, then $I_- \bigcap I_+ = \emptyset$ and the initial problem reduces to the problem of project selection from the set $I_0 = I \setminus (I_- \bigcup I_+)$. So far as the included projects (belonging to the set I_+) are supposed to be completely financed, the remained financial fund reduces to $C - \sum_{i \in I_+} c_i$.

As was already underlined above, the values of the projects, generated as a result of the multicriteria analysis, may be positive, zero or negative numbers. At the same time, it is clear (proceeding from the problem statement), that it may turn out to be reasonable to finance any of the proposed projects, independently of the sign of its value.

Thus, the values of the projects can not be directly applied at this phase and require some preliminary transformation. In order to make this transformation, two additional projects — ideal project $\bar{i}$, and anti–ideal project $\underline{i}$ are considered. It means, that for any $i \in I$ the following equalities hold:

$$\nu(\bar{i}, i) = 1;$$

$$\nu(i, \underline{i}) = 1,$$

i.e. the ideal project strictly prevails over any other project from the set I, while anti–ideal is strictly predominated by each of them.

Denoting by $\hat{I}$ the extended set of the projects,

$$\hat{I} = I \cup \{\underline{i}\} \cup \{\bar{i}\},$$

we shall obtain the following evaluations for preference intensity of an arbitrary project $i_1 \in I$:

$$1 < \hat{\varphi}^+(i_1) = \sum_{i \in \hat{I}} \nu(i_1, i) < N - 1,$$

$$1 < \hat{\varphi}^-(i_1) = \sum_{i \in \hat{I}} \nu(i, i_1) < N - 1.$$

Then for the net intensity of preference we get the limits:

$$1 - N < \hat{\varphi}(i_1) = \hat{\varphi}^+(i_1) - \hat{\varphi}^-(i_1) < N - 1.$$

Redefining now the values of projects v_i $(i \in I)$:

$$v_i = \frac{1}{2}\Big[1 + \frac{\hat{\varphi}(i)}{N-1}\Big]$$

we shall get positive numbers on the interval $(0, 1)$, which now can be applied in the corresponding optimization problems.

The concrete aspect of the optimization problem which should be solved depends directly on the selected policy of financing. Each financing policy determines the appropriate objective function, as well as the restriction the problem. As already was mentioned above, the choice of a policy of financing determines in particular if:

- financing of the projects proportionally to their costs (or values) is supposed;
- partial financing of the projects, included in variant of plan is allowed;
- direct values of the projects or values devided to their costs and terms of fulfilment (the so called specific values) are to be used in calculations;

- relations of competition and/or complement has to be taken into account

while working out a variant of portfolio.

In the case, when financing of the projects proportionally to their costs is supposed, the corresponding problem is given by the following form:

$$\sum_{i\in I_0} c_i x_i \ \to max$$

$$\sum_{i\in I_0} c_i x_i \le C - \sum_{i\in I_+} c_i;$$

$$x_i = x_j, \qquad i,j \in I_0;$$

$$0 \le x_i \le 1, \quad i \in I_0.$$

This problem has the immediate solution:

$$x_i = min\left\{1,\ (C - \sum_{j\in I_+} c_j)\Big/ \sum_{j\in I_0} c_j\right\} \qquad \text{for } i \in I_0.$$

The problem, corresponding to financing proportionally to values of the projects, has the same form, with the exception of restrictions–equalities, which in this case are:

$$\alpha_i c_i x_i / v_i = \alpha_j c_j x_j / v_j, \qquad i,j \in I_0,$$

where for all $i \in I_0$

$$\alpha_i = \begin{cases} 1, & \text{for the values of the projects,} \\ \frac{1}{c_i t_i}, & \text{for the specific values.} \end{cases}$$

The solution of the corresponding problem is

$$x_i = min\left\{1, \alpha_i (C - \sum_{j\in I_+} c_j) v_i \Big/ (c_i \sum_{j\in I_0} v_j)\right\} \qquad \text{for } i \in I_0.$$

The project portfolio generated pursuant to other policies of financing reduces to the problem

$$\begin{aligned} &\textstyle\sum_{i\in I_0} \alpha_i v_i x_i \to max \\ &\textstyle\sum_{i\in I_0} c_i x_i \le C - \sum_{i\in I_+} c_i, \end{aligned} \tag{1}$$

adding every time the appropriate restrictions.

So, if the proportional financing is excluded, the selection of projects is connected with the problem (1) with additional restrictions

$$0 \le x_i \le 1, \qquad i \in I_0$$

for the case, when partial financing of the projects is allowed, and

$$x_i \in \{0,\, 1\}, \qquad i \in I_0$$

otherwise.

If the chosen policy of financing assumes the consideration of the relations of competition between projects, the corresponding problem is supplemented with the restrictions:

$$\sum_{i\in I_l^c} x_i \le 1, \qquad l = 1, \ldots, n_c;$$

$$x_i x_j = 0 \quad \text{for all} \quad i, j \in I_l^c,\ i \ne j \quad \text{and} \quad l = 1, \ldots, n_c.$$

Finaly, for the case, when the relation of complement between the projects have to be taken into account, the correponding optimization problem remains the same. The difference from the other cases consists in that if some of complement groups are not included completely in a variant of project portfolio, then the decision maker should make a decision concerning the inclusion of the corresponding projects and the problem solution is renewed under new conditions.

Thus, in the case when the relations of complement between the projects have to be taken into account, the optimization problem is solved in several steps, specifying each time the restrictions.

The output data gives the following information pertaining to the generated portfolio of projects:

- set of projects included into the current variant of portfolio;
- financing portions of accepted projects relatively to their costs;
- the correspoding policy of financing;
- value of the global index wich characterizes the current variant of portfolio, i.e. the value of the corresponding optimization problem;
- total cost of accepted projects;
- period of fulfilment of the program determined by the generated variant of portfolio;
- remaining financial resources;

Concerning complexity of soluble problems it is possible to note, that in the case, when the policy of financing allows partial financing of the projects, the corresponding optimizstion problems do not present any difficulty at their solution. The situation is essentially complicated in the case, when the policy of financing does not assume an opportunity of partial financing of the projects. The solving of problems in these cases requires large resources of time and memory. In order to solve more effectively these problems the algorithms, based on principles of dynamic programming (e.g. [22],[23]), modified and adapted to corresponding particular problems are used. They include a number of filters in order to reduce at each iteration the set of possible portfolios.

The variant of project portfolio (with their appropriate portions of financing) obtained at this stage is put forward on evaluation to the decision maker, which can bring it to an appropriate aspect, including or excluding some of projects, or to get new variants of the portfolio, revising the financing policy, weights of the criteria, etc.

5 Practical Implementations and other Approaches

The decision support system, considered in this paper, was developed and implemented on a IBM PC compatible computer by the OR Group. It was applied to analyze the scientific and technical projects and to generate variants of portfolio, submitted for financing in the framework of institute.

The problem of multicriteria decision making, and R&D project research in particular, still remains one of the central problems for the OR Group. A somewhat different approach to the calculation of project value can be found in [24] and [25], dedicated to the same R&D project selection problem. The method described here make use of the mean ranks discussed in [27] and does not need the determination of weights of criteria. In that case the relative importance of criteria are defined through a preference structure, specified by a total preorder. An alternative aproach is given in [26], where the values of projects are evaluated using theory of fuzzy numbers.

The DSS for R&D project monitoring, recently developed by the same OR Group, is an attempt to deal with a more general problem, when the control of the realization of projects is assumed. In this case one need to consider the new projects as well as the uncompleted projects accepted during the previous years. The portfolio for the current year is calculated under the assumption that some of projects being financed (in correspondence with the portfolios of previous years) can be dropped as a consequence of their unsatisfiable development. Hence, this approach to R&D project selection problem will assure a more efficient control of disposable financial resources.

Many of capabilities of the decision aid systems can be provided simultaneously and interactively by the software package for multicriteria analysis and discrete optimization, worked out also by OR Group. A brief description of this tool can be found in [28]. The package allows to solve the problems of multicriteria analysis, as well as the multiobjective problems. In order to solve the problems of first class this package includes a range of methods like ORESTE, ELECTRE and others, providing the total and/or partial preorders on the given sets of actions. As for the discrete optimization problems, the package allows the user to get the Pareto–efficient solutions, providing for that purpose several numerical algorithms.

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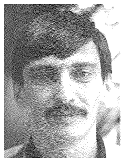

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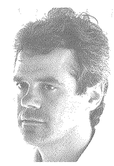

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