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Selection and Evaluation of Innovation Projects

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SELECTION AND EVALUATION OF INNOVATION PROJECTS

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1. INTRODUCTION

This working paper presents the first step of an ongoing research project which will be continued during the next few years at the University of Economic Sciences in Berlin.

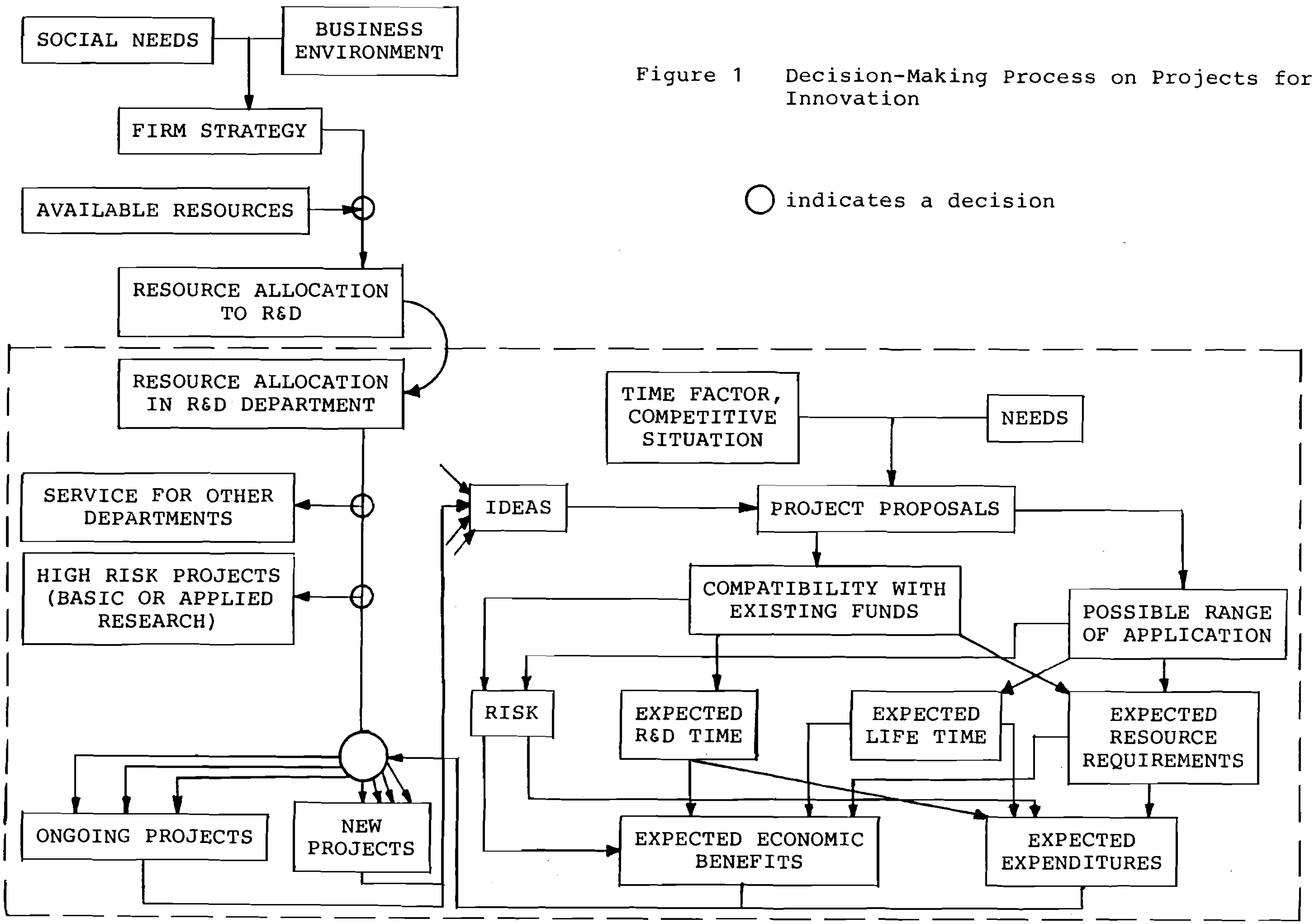
The subject of this paper is the decision-making process for decisions on innovations. During the past three decades considerable efforts have been devoted to investigating the role and importance of innovations for the growth and prosperity of firms both in market and planned economies. Effective management of innovations is a decisive factor in their development. A certain increase of funds devoted to R&D does not result in an appropriate increase of output in terms of productivity. Problems of an "optimal" management of innovations are investigated in many countries.

The scope of this study is indicated by a broken line--see Figure 1. A model proposed in this paper will formally enclose only the resource allocation for a set of ongoing and new projects.

The study was initiated by decision-makers of a particular industrial branch in the GDR. An analysis of the advantages and disadvantages of the decision-making process revealed the necessity of a decision support system. The approach developed is tailored to the case study but is general in several aspects.

Figure 1 Decision-Making Process on Projects for Innovation

○ indicates a decision



This paper describes a model for resource allocation in R&D which is well suited for our case study. The choice of the model type was based on an analysis both of the decision-making process in the particular firm and of existing models for this purpose.

A combination of innovation theory and economic-mathematical methods for aiding decisions is from our viewpoint a necessary condition for a successful development and implementation of a system we are aiming at.

A system of this kind will improve the decision-maker's understanding of the relationship between the long-term development of the firm and the resource allocation in R&D.

2. INNOVATION THEORY AS A BASIS FOR DECISION-MAKING ON PROJECTS FOR INNOVATIONS

Innovation is a complex phenomenon, including all spheres of technological, economic and social activity. We cannot hope to grasp all these activities of different natures in one quantitative model. Moreover, it is questionable whether such complex models would really assist the decision maker to arrive at better decisions.

From our viewpoint the effect will be better if one tries to include some crucial qualitative aspects of innovations in the form of judgments concerning expected future states of the world.

In order to take "good" decisions, the decision maker must rely on careful analyses of past experience and past trends. Many factors influence the development of innovations, and they all act in a space with at least three main dimensions:

-- innovator
-- organization
-- environment.

No list of factors influencing innovations is exhaustive, but a brief survey of them will make us aware of the value and shortcomings of models proposed in the literature for aiding decisions on innovation projects (including our own approach). (For details see Haustein, et al., 1980.) Figure 2 can be used as a guideline for identification and classification of the influencing factors.

INNOVATOR

(a) Input, output

a1 Input related factors: necessary quantities and qualities of input (production) factors

a2 Output related factors: knowledge and utilization of the properties and applicability of the technique

(b) Interplay of innovative persons

b1 Interplay of the functional roles which have to be fulfilled to accomplish innovative activities

b2 Characteristics of innovative persons who play the roles

ORGANIZATION

(c) Resources

(d) Organizational dimensions

d1 Relationships with the environment

d2 Internal dimensions

(e) Organizational measures

e1 Planning measures

e2 Control measures

ENVIRONMENT

(f) Resources

(g) Environmental dimensions

g1 Economic sector

g2 Political sector

g3 Social sector

(h) Environmental measures

h1 Economic sector

h2 Political sector

h3 Social sector

Figure 2

The groups of factors are listed below. Each factor governs the innovative activities in a specific way; this influence is likely to be dependent on certain circumstances. No general pattern of influence can be found. Some factors can be inhibiting or promoting in dependence on the specific situation. The weight of influence changes over time and depends on the stage of a particular innovation. The concept of the efficiency of the factors is a mixture of evidence from empirical studies, results of theoretical reasoning, plausible arguments, and sheer truism. Hypthoses about the efficiency of a more detailed list of influencing factors are presented by Haustein, et al (1980).

What we have to examine in this paper are the factors which can be included formally in the model proposed here. It is theoretically not difficult to include such input and output related factors like labor, capital equipment, raw materials, technological risk, unit scale, financial funds. Some relations with the business environment can be fairly accurately modeled. But many other factors remain outside of all models for project evaluation and selection reported in the literature, for instance, interplay of functional rules, characteristics of innovative persons, the economic mechanism and management system. This refers also to most factors of the political, social and economic sectors. We consider the above listed shortcomings of any model for decision support to be theoretically, rather than practically, important because the decision maker of a parficular firm is not very concerned about most of the factors mentioned. In his daily work he has to deal more with the input and output related factors.

With the model developed in this paper we try to look at the rather early stages of an innovation project, when only rough predictions exist about the level of technology and the range of application. Some of the most important relations between these early predictable characteristics of an innovation project and other variables are presented in Figure 1. One gets a first idea about an innovation project, intended to be realized in Table 1, which reflects an attempt to measure both the range of possible application and the scientific-technological level in specific scales.

1

NO	Scientific-Technological Level	V_k	Quantitative growth of existing demand	existing demand (Improved parameters of existing products or processes)	modification of existing demand (New parameters of existing products and processes)	Arising of a new demand (new product or process) in the existing demand complex	Essential modification of existing demand complex by new products or processes	Arising of a new demand complex or subcomplex	Change of the whole system of needs
	ik		1,0	1,5	2,2	3,2	4,6	6,8	10,0
1	Quantitative growth of the existing technical basis	1,0	1	1,5	2,2	3,2	4,6	6,8	10,0
2	Improvement within well-known technical principle	1,5	1,5	2,3	Bentwood Furniture 3,5	Bicycle 4,8	6,9	10,0	15,0
3	As 2 but with essential changes of 1 factor (mats., tool, function design)	2,2	2,2	Oxygen process 3,3	Thomas process 4,8	Diesel engine 7	Paper production 10	15	22
4	As 3 but with ess. changes of sev. factors	3,2	3,2	4,8	Stitching bond 7	Atomic ice-breakes 10	Electrical railway 15	22	Spinning Jenny 33
5	New solutions within well-known basic principle	4,6	4,6	6,9	Gyrocompass 10	Polyethylene 15	Detergents 22	Vacuum lamp 33	46
6	New basic principle within same form or struc. level of the matter	6,8	6,8	10	15	22	Synthetic fibres 33	Incandescent lamp 46	68
7	New basic principle changing form or struc. level of the matter.	10,0	10	15	22	33	Radar 46	Transistor 68	Electricity 100

Compatibility with existing funds, which is an indicator of the scientific-technological level of an innovation, and the range of application determine the next set of variables (the specific form of this determination can be only roughly evaluated):

-- risk
-- R&D time
-- expected life time
-- expected resource requirements (see Figure 1).

These four variables cannot be predicted precisely at the first stages of the innovation project but the estimates become more and more accurate with the progress of the project. The same refers to the expected economic benefits and the expected expenditures of a particular project.

One has to take into account both the efficiency of the firm producing the innovation and applying it because the speed of adopting a new product or process depends greatly on the savings on the consumer side. In a centrally planned economy we speak about the socio-economic efficiency of innovations and about the socio-economic optimum we are aiming at (see for a survey and discussion of this topic Danilov-Danilyan, 1980).

3. CHARACTERIZATION OF THE FIRM OF OUR CASE STUDY

3.1 Problem Formulation

The problem under consideration can be formulated in the following way:

(a) Which projects of the set of possible proposals should be chosen in order to meet the goals both of the firm and of society as a whole?

(b) How much should be allocated? This decision also includes rejection, postponement, termination or acceleration of ongoing or new projects.

The decision is subjected to several constraints. First, the company cannot exceed the amount of resources (including manpower) currently available or expected to be available in future planning periods. Second, some projects are mandatory and have to be adopted in contradiction to their expected economic benefit. These projects are necessary to maintain a market position or to overcome bottlenecks in the production process. Third, the ongoing projects should be distributed over the stages of innovations in order to avoid demand peaks of certain resource types and to maintain continuity in the firm. Fourth, one has to adopt a portfolio of projects which combine in a special way innovations of certain classes (see Haustein and Maier, 1979).

3.2 Objectives

Let us briefly consider the objectives of the firm under consideration. As a result of discussions with the R&D management we decided to include in the first step of the analysis of the decision making process and the design of a decision support system tailored to the particular needs of our firm, three objectives:

1. maximization of profits
2. maximization of exports
3. maximization of a parameter, characterising consumption.

The objectives were chosen in accordance with the existing economic mechanism in the GDR. It is obvious that the objectives listed above conflict with one another. This problem will not be dealt with in our paper. The conflict is more or less strong in the dependence on the attainment level, which complicates the problem considerably.

From our viewpoint there is no sense in including all objective functions of little importance because of two reasons: (1) people tend to select alternatives which are superior in the more important dimensions (Slovic, et al 1977); (2) often formal complication of the analysis does not improve the decision maker's understanding of the decision situation.

3.3 Types of Innovations Prevailing in the Firm

The choice of a model type depends critically on which have to be characterised. The firm under consideration is the only producer of commodities of a special kind in the GDR. It has about 15,000 employees. The technical field represented by our company is relatively small and not difficult to survey. There are about 10 basic products stemming from relatively "old" basic innovations. Most of the R&D projects can be summarized under "improvement innovations". The percentage of basic research projects is small and we can consider it negligable. Many projects are characterised by relatively well defined technical and commercial parameters. Hence decisions to be taken on innovation projects are not unique. They have some common features. This fact is very important for the method to be chosen. The disposal of innovation projects in accordance with the classification of innovations developed in Haustein and Maier (1979) is crucial for the understanding of the benefits which might be expected from a particular project. This concept distinguishes between basic, improvement and pseudo-innovations (for a more detailed classification see Figures 3 and 4). Another important aspect reflecting the essence of an innovation can be added by distinguishing between push, compensation and continuation process (see Haustein, 1974).

Typical patterns of the development of efficiency are depicted in Figure 5. These thoughts are more related to the level of R&D strategy formulation (see Figure 1) than to the direct management of a portfolio of projects, but influence management in a number of ways. Management has to find a "good" mixture of projects yielding short-term as well as long-term benefits. It is almost impossible to define what a "good" mixture is. An accurate analysis of what was a good mixture in the past is rendered more difficult by the fact that information about previous projects is wide spread over several departments of the firm under consideration in this report. So in this question we have to rely exclusively on the experience of the decision-maker.

In the firm under consideration, corporate strategy is greatly influenced by decisions on the level of the Council of Ministers, which determine the goals in the field of energy saving. The principal structure of the decision making process on innovations is given by law in the GDR, which defines the main decision points and the necessary documents and expertise to be presented as well as the members of the expert committee, who take the decision.

No.	Type B	Fundamental Research Share	Applied Research Share	Range of Application	Push on Production System	Examples
1.	Major Basic I. BI1	High	High	Change of the whole system of needs and its	Change of the whole production system	Use of Micro-electronics new energy systems
2.	Middle Basic I. BI2	Middle	High	Establishing of a new demand complex (or market)	New package of industrial branches	Use of Micro-processors Nuclear energy
3.	Minor Basic I. BI3	Low	Middle	Essential modification of existing demand complexes	New industrial branches	Use of fast breeders

Figure 3

No.	Type	Fundamental and applied research share	Development share	Range of application	Impact on production systems	Examples
1.	Very important II1	Middle	High	New demand. New product in an existing demand complex	New industrial subbranches	Use of polyester
2.	Important II2	Low	Middle	Essential modification of the demand complex. New parameters of well-known products	New product lines or processes	Use of Thomas Steel process Electric toothbrushes
3.	Normal II3	No	Low	Simple modification of existing demand. Improved parameters of well-known products	Improved product lines or processes	Flouride toothpaste
4.	Small changes II4 (Marginal II)	No	No	Low improvements	Low improvements	Better touch-on telephones

Figure 4

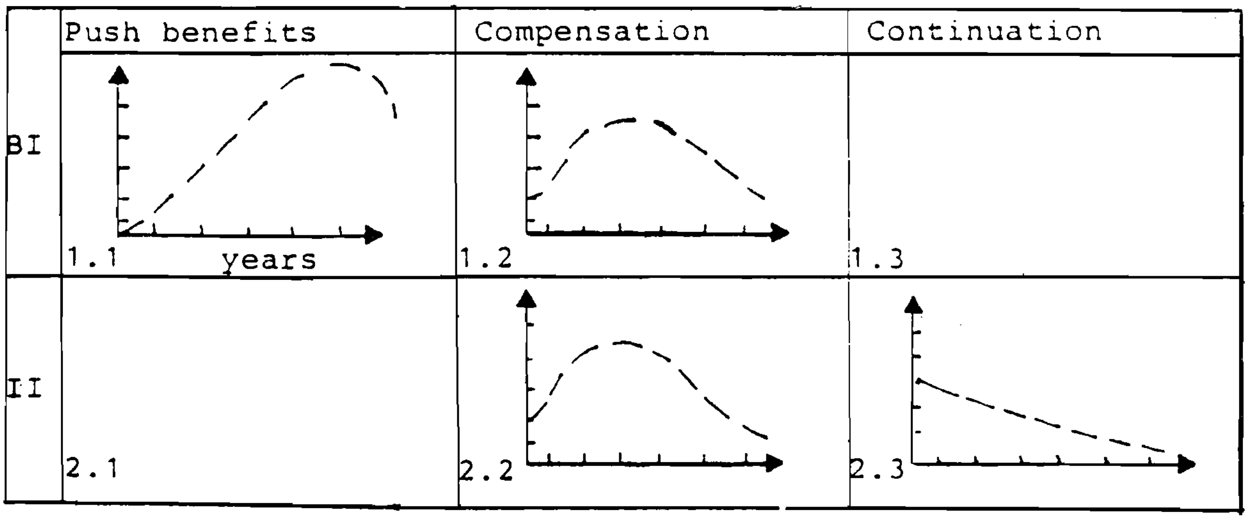


Figure 5   Typical Benefits of BI and II

The fact that the firm considered in this paper is the only producer of some specific products in the GDR makes the application of the concept of relative efficiency to our case study more difficult, but not impossible. This concept is being developed in the Innovation Task Group of MMT at IIASA and was started in the early 70s. (For details see, for instance, Haustein, 1974; Maier, 1979; Haustein, Maier and Uhlmann, 1980--in preparation.) It represents the third phase of the development of innovation theory (Maier, 1979) and can be summarized in the following way. In the 60s management scientists and economists were primarily concerned with the "optimal" management of R&D and the improvement of the linkage between the stages of an innovation. These investigations have not lost their actuality and their results need to be reconsidered on the basis of new insight into the forces, governing innovation processes obtained in the third phase of the development of the theory.

The new aspect added was the relationship between innovations and efficiency. Efficiency and innovations are not identical items.

> To understand that, it was necessary to investigate more carefully the development of the efficiency of the production unit, which has adopted the innovation, in comparison with the average efficiency of all production units as a whole in the production field. (Maier, 1979).

The exploitation of this concept is more difficult when only one firm monopolizes the field. The transmission of the concept to the international level of investigation seems to be almost impossible because of the lack of data necessary to perform it.

Information on international developments and trends is fed back to our particular firm only with considerable time delays and in a form badly suited to comparisons of relative and average efficiency. Data obtained on international fairs, prices, etc., are a bad indicator for the progress made by competing firms, but must be used as a basis for efficiency estimates.

The ratio of relative and average efficiency and its development over time is crucial for the innovation strategy of a particular firm, serves as a specific background for decisions to be taken on innovation projects preferred (important, normal or marginal improvement innovations, for example).

4. DECISION MAKING (DM) ON INNOVATIONS WITH A DECISION SUPPORT SYSTEM (DSS)

We shall now briefly characterize the features of innovation decisions, which will influence the choice of an appropriate model approach.

(a) Decisions on innovation can be reversed only with considerable losses of efficiency. The more an innovation advances, the more difficult it becomes to reverse the decision to adopt it because of the manpower involved.

(b) Innovation decisions combine problems of all economic activities of a particular firm, for instance, investment policy, the hiring of manpower, procurement policy, market strategy, etc. DM is subjected to many factors of different quality.

(c) High uncertainties concerning further development of the adopted projects, the future market conditions, etc., complicate decision making. Uncertainties involved in scientific and technological progress are not predictable contrary to the future business environment, which is generally characterised by long-term trends.

(d) Decision makers have to deal with multiple conflicting objectives representing both qualitative and quantitative business aspects. Measurement in terms of corresponding scales combines objective and subjective elements. The importance of experience represented in the firm of judgments cannot be overemphasised. The evaluation of alternatives in terms of the objectives can change rapidly as a result of unforeseen events.

(e) Innovations are created not by chemical reactions but by people. The people involved (decision makers, R&D specialists, workers) form groups with their own goals, which may differ considerably. In order to be successful, management must create an atmosphere of commitment for the eventually selected projects and weigh the interests of all groups.

(f) Innovation projects extend over about 3-7 years (in the firm under consideration). The innovation process includes all steps beginning with proposals and ending with the implementation of a certain product or process. (The methodology developed in this paper does not consider explicitly steps proceeding project proposals and following implementation). Hence, decision making on innovations is dynamic and multi-stage in nature. All stages have special problems and their own sources of uncertainty. Responsibility alters in accordance with the stage attained. A lot of partial decisions have to be taken in the iterative process of decision making during the development of a certain project. The understanding both of the feasible set of alternatives and the aspiration level of the objectives can be subjected to considerable change.

(g) Decisions on innovation projects have to be taken within a certain time period, sometimes rather quickly. Thus, we have to deal with a situation in which

decisions are made sequentially in time; the task specifications may change over time, either independently or as a result of previous

> decisions; information available for later decisions may be contingent upon the outcomes of earlier decisions; and implications of any decision may reach into the future. (Rapoport, A., 1975).

The eventual aim of the work reported in this paper is the development and implementation of a decision support system (DSS) suited for decision on innovation projects within a portfolio approach on the level of the R&D management.

In Keen and Morton (1978) a DSS is defined as computer-based support for management decision makers who are dealing with semi-structured problems. The problem of defining an "optimal" R&D portfolio is often considered as an unstructured one. But this depends on the features of the innovation decisions in each certain case. Important operations in this decision process are comparison of resource requirements and availabilities and assessments of the degree to which the new projects meet the goals of the firm under consideration. Thus innovation decisions require substantial search in information files on previous experience, application of analytic techniques. Some of the steps in decisions of this type can be partially delegated to the computer and solved in an interactive mode of operation.

The general approach of DSS starts with the investigation of the key decisions to be taken and with the definition which parts of the whole process are structured and which judgmental. Then the decision maker trys to automate structured subproblems on the basis of appropriate models. We believe that the approach discussed in this paper fits well into the concept of DSS. A decision analysis of the proposed innovation projects (based on decision trees) may serve as a convenient starting point of further analysis with other interactive procedures discussed later in this paper. The first step is closer to the rational framework of decision making, the second step tends more to the satisfying concept and will be closer to the real decision making situation. We do not understand DSS as a negation of widely accepted management tools but rather as an extension.

A decision support system based only on the outcome oriented approach is too narrow. As does, M. Zeleny (1976), we define a decision as a dynamic process with feedback loops, search detours, sequential exploration of the preference and the feasible set of alternatives, information gathering, reassessment of the structure and goals of the alternatives, with adding and removing of alternatives. An optimisation of such a complex system is only possible within a highly simplified model based on a long list of assumptions. Figure 6 presents a simplified version of the process oriented approach of decision making (for details see Zeleny, 1976).

A model with the pretension to be helpful in real life decision making should meet the requirements based on our discussion of features of innovation decisions. The requirements are listed in Figure 7.

Development, test and implementation of a decision support system for decisions on innovation is a time- and money-consuming process and includes several steps which differ in the degree of complexity of problem representation. The process starts with a relatively simple model and includes new aspects step by step.

5. MODELS FOR EVALUATION AND SELECTION OF PROJECTS FOR INNOVATION

5.1 Principles of Model Construction

To date no model has been constructed reflecting all requirements listed in Figure 7. Real evaluation and selection processes consists of at least two different steps. The first step is a qualitative screening of the innovation project proposals. Some ranking or scoring methods can help to reject all proposals which do not meet certain minimum requirements or which are obviously dominated. In this qualitative phase one can adopt risky basic research or applied research projects with highly uncertain economic parameters. A final decision on their continuation or rejection is delayed until some major uncertainties can be clarified or disappear.

The second step of evaluation and selection is quantitative in nature. The proposed methodology will be applied to support

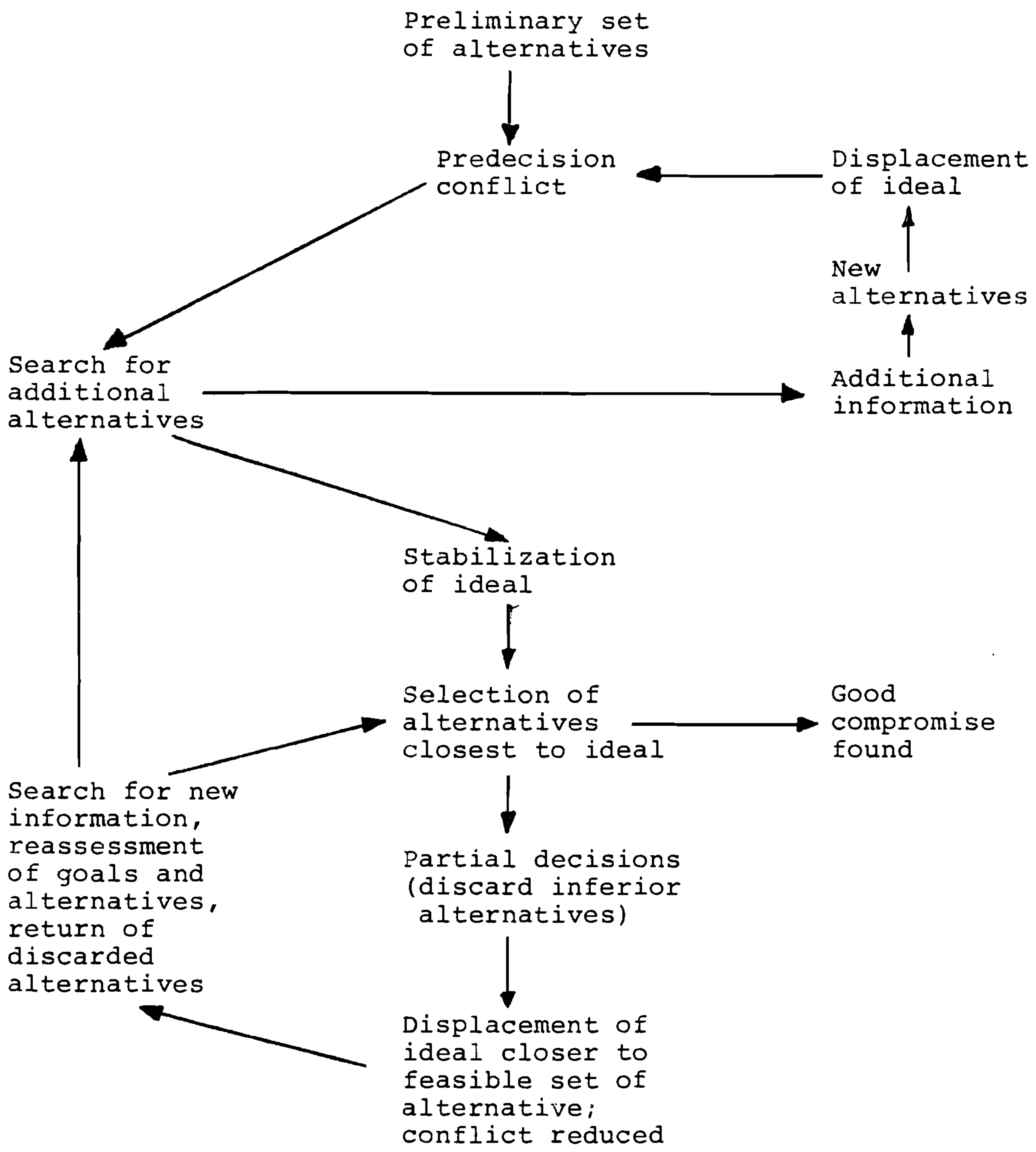


Figure 6 Simple process-oriented model of DM

(This Figure is based on the theory of the displaced ideal developed by Zeleny (1976); the ideal is defined as the alternative, infeasible in general, providing the highest score with respect to all individual attributes considered.)

A decision support system for decisions in innovation should:

- o Combine outcome-oriented and process-oriented approaches
- o Reflect the multi-stage nature of innovations,
  uncertainty,
  mutual dependence between projects,
  major kinds of resources,
- o Be suited for multiple objective decision making (MODM)
- o Be compatible (more or less) with the existing planning mechanism and management system
- o Reflect the impact of possible future sources of uncertainty on actual partial decisions
- o Be suited for interactive man-machine dialogue
- o Be based on easily accessible data
- o Be based on existing problem solving techniques which can be computerised easily.

Figure 7 Requirements for a Decision Support System the final decision. Evaluation and selection is a continuous process and has to be repeated whenever considerable changes occur. Our approach is based on decision trees. We are convinced that this methodology can be a useful tool for the decision maker to reflect the relationship between corporate strategy and resource allocation on new and ongoing projects, if it is combined with a firm model for forecasting of long-term effects of the adopted innovation projects. Such a model is being developed and tested.

Our approach is based on some principles, which are quite common for dynamic and complex situations (see, for instance, Belyaev, 1977). First, faced with a complexity of real world problems the decision maker and the analyst are forced to simplify reality to a certain degree. These simplifications refer to:

(a) the projects formally considered

(b) the time periods (model horizon and benefit horizon)

(c) the number of objectives and kinds of resources

(d) the decision maker

(e) the utility function

(f) the complexity of the real situation (interdependencies between several aspects).

Our model includes only medium and large projects. A fixed percentage of the budget is spent on all remaining R&D projects and on highly uncertain basic projects which sometimes cannot be related to particular products and processes or have ill-defined economic and technical parameters. R&D management is represented in our model by one decision maker. We assume his preferences to be typical for R&D management as a whole.

Most of the variables in the proposed model have continuous character. In order to handle the problems we perform a "discretization" of all continuous variables and functions (for instance, probability distributions) and consider only a limited number of options, in most cases not more than five, including mean values and extreme values. This simplification makes the very complicated assessment procedures of probabilities of future events much easier because the decision maker will be able to perceive significant differences between the options. The same refers to time. So we have time periods with a length of half a year.

In a dynamic environment with changing objectives, sets of feasible alternatives and preferences an optimization of the evaluation and selection process of innovation projects over the whole planning horizon is nearly impossible. Under such circumstances the principle of making priority decisions applies. The "optimal" solution refers only to the first time period. Decisions related to more distant time periods will be reconsidered when the information on them becomes more reliable. Decisions are divided into stages similar to the stages of innovations. This is the main idea of the law, defining the general structure of the decision making process on innovation projects in the GDR.

A decision on innovation projects cannot be taken on an individual basis, because all projects compete for scarce resources, especially for manpower and investments. For this reason we apply a portfolio approach. In order to find an approach appropriate for the problem formulated above we shall try to split our problem into existing classifications of decision situations, which will throw light upon possible difficulties in handling it. Danilov-Danilyan (1980) based his classification on (1) the description of the set of alternatives, (2) the description of the preference structure and distinguishes between four classes of decision situations (see Figure 8).

		DESCRIPTION OF ALTERNATIVES	
		GOOD	BAD
DESCRIPTION OF	GOOD	I	III
PREFERENCES	BAD	II	IV

Figure 8

In our case the number of feasible alternatives (project proposals) is well known, but their description in terms of resource requirements, development time, probabilities of technical and commercial success, short and long term effects on the firm under consideration and society as a whole is rather poor at least at early stages of the innovation process. Obviously preferences are defined even worse. Hence our problem belongs to class IV like almost all problems of socio-economic decision making. von Winterfeldt and Fischer (1975) classify decision situations on the basis of three features of the alternatives: multi-attributed, uncertain, time-variable (Table 2). The choice of an optimal portfolio of innovation projects is characterised by the presence of all three complicating features. Both references indicate, that appropriate models for our case are lacking at present. The only way to apply formal methods is to abstract from one of the features, for instance, from the time variability of the preference system.

Table 2 A classification of choice situations and models

Case	The choice alternative is			Models
	multi-attributed	uncertain	time-variable	
1	yes	no	no	1. simple order (model 1.1) 2. riskless trade-off models (1.2 and 1.3) 3. additive conjoint measurement (1.4)
2	yes	yes	no	1. simple expected utility model (2.1) 2. riskless decomposition - expected utility models (2.2-2.4) 3. multiplicative expected utility model (2.5) 4. additive expected utility model (2.6)
3	yes	no	yes	no model at present
4	yes	yes	yes	no model at present
5	no	no	no	1. simple order 2. difference structures
6	no	yes	no	1. EU and SEU models 2. minimax and minimax regret models 3. portfolio theory
7	no	no	yes	1. additive time preferences 2. additive time preferences with variable discounting rates 3. additive time preferences with constant discounting rates
8	no	yes	yes	1. additive time preferences - expected utility model (constant or variable discounting rates) 2. multiplicative time preferences - expected utility model (constant or variable discounting rates)

5.2 Evaluation of Existing Models

Models for project selection and evaluation have been reviewed elsewhere (see Schwartz, 1976; Clarke, 1974; Souder, 1978; Souder,1973a and b; Gear, Lockett and Pearson, 1971) and have been classified by Moore and Baker (1969), Souder (1972), Gear, et al (1971) and others. We shall summarize the most important issues here.

(a) Only a very few formal models are actually in use. Some successful implementations of project evaluation models are reported in Grossman & Gupta (1974), Atkinson & Bobis (1969), Cochran et al (1971), Souder (1968), Bell (1970).

(b) Ritchie (1970), Rubenstein (1966), Baker and Pound (1964) found the reasons for the manager's ignorance of almost all proposed models:

- -- lacking or inadequate handling of important aspects in the DM process (for instance, uncertainty, sequential nature of DM, dependencies between projects, multiple criteria)
- -- inability of existing models to reflect the real evaluation and selection process, the role of experience, intuition and judgment
- -- lack of needed input data
- -- lack of mutual understanding between decision makers and analysts.

5.3 Decision Tree as a Basis of the Proposed Model

Recent developments in R&D porfolio selection and evaluation models are encouraging (see Allen and Johnson, 1971; Hespos & Strassman, 1965; Gear et al, 1970; Lockett & Freeman, 1970; Gillespie & Gear, 1972; Gear et al, 1972; Lockett & Gear, 1972; Gear & Lockett, 1973; Gear, 1974; Chiu & Gear, 1979). Clarke (1974) stated that models involving decision tree analysis have been receiving increasing attention by management scientists. Based on a comprehensive literature survey we came to the conclusion that a model using decision trees is best suited for our specific purpose.

A decision tree is a convenient tool to structure all notions of a decision maker about a project. (We will return to this question from a theoretical standpoint in section 6.5.) With its help one can represent and analyse a series of partial decisions to be made over time. So decision trees reflect one of the most important features of innovation decisions—their sequential character. A formal method based on decision trees can be applied successfully only when the innovation projects to be represented reach a certain degree of maturity resulting in relatively well defined notions on basic construction, project versions, resource requirements, main sources of uncertainty, development on a time scale, etc. We assume that projects are evaluated and selected over a certain planning horizon, divided into T time periods. A decision has to be taken on N projects, each of them with j versions of completion ($j = 1 \ldots j_i$). Projects can branch out whenever decision nodes or chance nodes occur. A decision node on the time scale represents a point where the decision maker can influence the further development of a project under consideration by taking a decision from which a branch of a given set will be selected. Chance nodes are not under the control of the decision maker. Their outcome depends on chance events like, for instance, rise of prices on raw materials, supply of necessary machinery in a certain time period. The length of the time periods in the model can be chosen in a way that without limitations of generality we can assume that decisions on the innovation projects are taken in the beginning of the period. The same assumptions refer to chance events which are supposed to occur before a partial decision is taken. For each time interval and each project version the resource requirements are assumed to be known. The number of resource types and their kind is specific for a particular case.

Another model assumption requires that the decision maker is able to assign probabilities to the chance outcomes of a chance node. This problem will be discussed later. All combinations of particular decisions and chance events have some outcome associated with them which are measured in scales corresponding to the chosen multiple objectives. The presentation of innovation projects in the form of decision trees has several advantages. Some of them are listed in Figure 9.

Schwartz and Vertinsky (1980) found, that the selection of R&D projects rests most of all on consideration of certain project specific characteristics, such as probability of success (technical and commercial), rate of return, payback period. More general economic indicators are often ignored.

> R&D decision making is ... stimulated by the opportunity of particular R&D projects rather than being part of an integral environmental adaptation stratey.

This finding is an argument for the application of decision trees for the selection and evaluation of innovation projects, because they reflect project-specific attributes much better than environmental ones.

-- One can look at all projects as a whole

-- Representation and adequate handling of interrelated decisions at different points on the time scale

-- Abstraction from all less important project features

-- Decision maker is forced to present in an interactive manner notions, judgment, experience, intuition, quantitative data to construct decision trees

-- Early detection of feasible options, bottlenecks

-- Reflect mutual dependencies between partial decisions and main sources of uncertainty involved

-- Combination of outcome- and process-oriented approach of decision making.

Figure 9 Advantages of Decision Trees for Presentation of Innovation Projects

On the other hand we cannot overlook several weaknesses and problems in the application of decision trees to improve the selection and evaluation of innovation projects.

(a) Decision trees cannot reflect the whole complex of factors influencing the real decision making process. This refers, moreover, to all quantitative models. It is very difficult and subjective to build qualitative factors in the decision tree. The problem whether it is possible or not to apply decision trees to the situation described in this paper is discussed in the literature. Larichev (1979), for instance, questions the value of a decision tree analysis for unique decisions. On the other hand there are a lot of applications even to problems of this kind (see Keeney and Raiffa, 1976; Bell, Kenney and Raiffa, 1977; Operations Research, Vol.28, No.1, Jan-Feb. 1980).

(b) The construction of a decision tree is time consuming. All data is needed at the same time. Often decision makers are not willing to spend the time necessary and to answer the analyst's questions about their preference system.

(c) It is extremely difficult to construct decision trees for cases where their application is most promising--for basic research and applied research topics at early stages of their development. A certain degree of confidence in both objectives and technical/commercial parameters of the projects is required.

(d) Some methodological problems have to be solved in a specific way for each case. Among these are, for instance:

   -- inclusion of new project proposals in future time periods,

   -- length of planning horizon (problem of projects which are not completed by the end),

   -- interdependences between several projects,

-- transfer between some different resources,

-- degree of detail of the decision trees

(e) Decision trees do not take into account strategic considerations which might greatly influence the selection of innovation projects. Not all important aspects of decision making on innovation projects are quantifiable. For this reason mathematical models for project selection may be misleading in some applications (see Roman, 1980).

(f) Decision trees cannot reflect the whole lifetime of an innovation. It is impossible to specify the resource requirements over 5-7 years ahead. The kinds of resources required for an innovation differ considerably from stage to stage. Hence the analyst is forced to aggregate and looses a great part of the information available. Only rough numbers can be calculated with a model based on decision trees. But this refers to all economico-mathematical models pretending to support innovation decisions.

(g) Sometimes decision trees create the illusion of a freedom of choice which does not exist in real life because of the constraints which were not formally included in the analysis.

(h) The basic model is linear (see Section 7).

One could probably add some more limitations of the approach described in this paper. Despite all shortcomings we are convinced that the model can be useful not only in the specific case discussed here.

Smallwood and Morris (1980) used decision trees only to structure the decision to be taken, but generated the numbers with underlying and interconnected mathematical models. First attempts to realise this idea were reported by Gear et al (1970).

The following conclusion can be drawn. Not all problems can be solved applying the proposed methodology. Other models and techniques which are widely accepted in industry have to be used as an information input of the described dynamic multi-stage method for project evaluation and selection, for instance:

-- diffusion models of innovations (see Mansfield et al, 1971; Davies, 1979),

-- models for forecasting manpower requirements,

-- models of technological substitution (see Linstone and Sahal, 1976),

-- models for optimal timing of innovations,

-- scenario analysis and others.

We will take first things first and concentrate our attention on the basic model.

6. COMPARISON OF MODELS FOR MULTI-OBJECTIVE DECISIONMAKING (MODM)

6.1 Classifications of Models for MODM

Almost all models for innovation project evaluation and selection operate with only one objective. Discussions with decision makers of the company of our case study revealed the necessity to include at least three objective functions listed above. The objectives are non-commensurable. Thus, the question arises which methodology for multiple objective decision making is best suited for our case study. We will discuss this question in Section 6. Excellent literature reviews on multiple objective decision making were carried out by MacCrimmon (1973), Hwang et al (1980) and many others. Classifications of multiple objective decision making models provided by MacCrimmon (1973), Larichev (1979) and Hwang et al (1980) will throw light on our problem of choice because they are based on different classification principles.

MacCrimmon (1973) stresses structural differences between several methods (see Figure 10), Hwang (1980) the stages at which the information is needed and the type of information (Figure 11) and Larichev (1979) the type of information provided by the decision maker and the mode if its usage (Figure 12).

A. WEIGHTING METHODS

1. Inferred preferences
   (a) Linear regression
   (b) Analysis of variance
   (c) Quasi-linear regression
2. Directly assessed preferences: general aggregation
   (a) Trade-offs
   (b) Simple additive weighting
   (c) Hierarchical additive weighting
   (d) Quasi-additive weighting
3. Directly assessed preferences: specialized aggregation
   (a) Maximin
   (b) Maximax

B. SEQUENTIAL ELIMINATION METHODS

1. Alternative versus standard: comparison across attributes
   (a) Disjunctive and conjunctive constraints
2. Alternative versus alternative: comparison across attributes
   (a) Dominance
3. Alternative versus alternative: comparison across atrributes
   (a) Lexicography
   (b) Elimination by aspects

C. MATHEMATICAL PROGRAMMING METHODS

1. Global objective function
   (a) Linear programming
2. Goals in constraints
   (a) Goal programming
3. Local objectives: interactive
   (a) Interactive, multi-criterion programming

D. SPATIAL PROXIMITY METHODS

1. Iso-preference graphs
   (a) Indifference map
2. Ideal points
   (a) Multi-dimensional, non-metric scaling
3. Graphical preferences
   (a) Graphical overlays

Figure 10 Multiple Objective/Multiple Attribute Decision Models (Source: MacCrimmon, 1973).

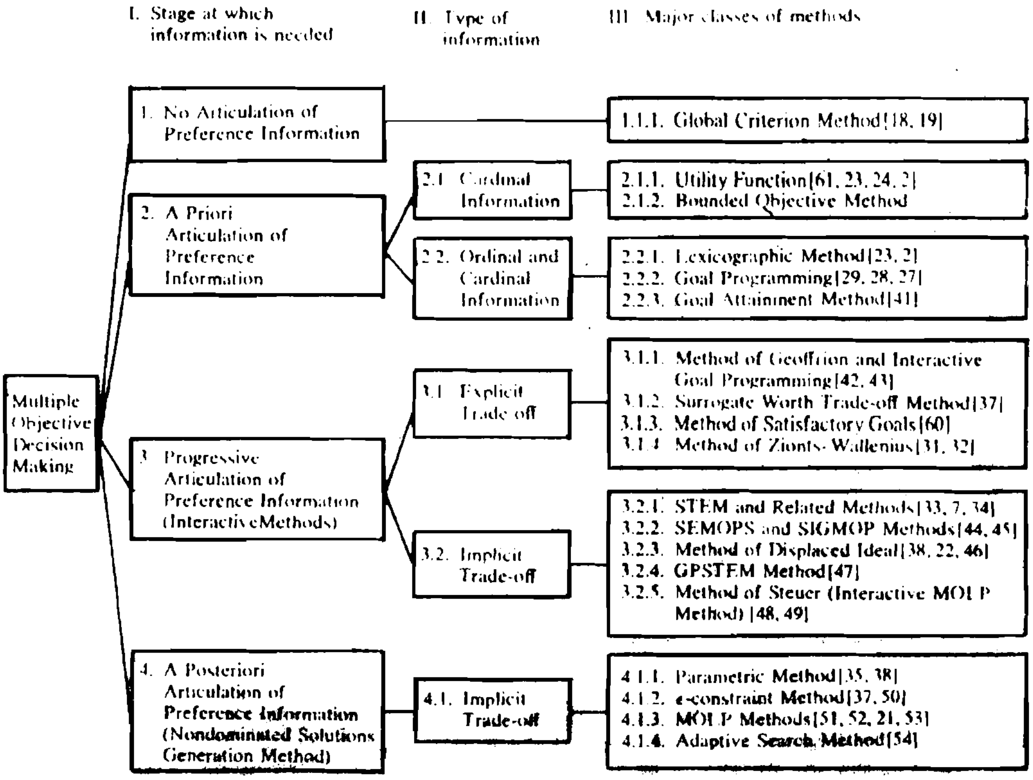


Figure 11 A taxonomy of methods for multiple objective decision making

(Source: Hwang et al, 1980).

Class	Basic Idea
1. AXIOMATIC methods	Several axioms are introduced and their validity is tested in order to construct a multiattribute utility function of a specific type (von Winterfeldt and Fischer, 1975; Humphreys, 1977; Keeney and Raiffa, 1976).
2. DIRECT methods	Decision maker prescribes the form of the aggregation function for the measurement (or assessments) in terms of the individual objectives
2.1 Prescription of both the form of the aggregation function and all its parameters.	
2.2 Application of specific criteria (Savage, Wald, Laplace, Hurwicz) in dependence of the attractive power for the decision maker under conditions of unknown probabilities of the states of the world.	
2.3 Postulation of the aggregation rule, but parameters are determined by the decision maker.	
2.4 Postulation of the aggregation rule; parameters are determined by calculations.	
2.5 Postulation of the rule of maximization of expected value (utility).	
3. COMPENSATION methods	Decision maker defines step by step a compromise between the objectives
4. Method of the thresholds of incomparability	Comparisons among the alternatives are made in pairs and for each criterion separately. An index is calculated and tested against 3 thresholds set by the decision maker. The relationship between alternatives is determined as "strongly preferred to", "weakly preferred to" or "no preference". A ranking is developed from the preference matrix. (Roy, 1971, 1977; Larichev, 1979).
5. INTERACTIVE Methods	(Discussed in Section 7)

Figure 12 Larichev's classification of multiple objective decision making methods

A first glance of the models proposed in the literature indicates that the following model classes are worth considering in our context:

-- global criterion method models (section 6.2)

-- goal programming (section 6.3)

-- STEM (section 6.4)

-- models based on decision analysis (section 6.5)

-- reference point approach (section 6.6)

-- method of thresholds of incomparability (section 6.7)

We will briefly consider weaknesses and strengths of the models listed above, in order to define possible options for our case study. We are convinced that not just any model will solve all the problems. For this reason we will try to implement two or three of them and compare the results obtained.

6.2 Global Criterion Model

The objective function is postulated in the form

$$\min_{x} F_k = \sum_i \left(\frac{fi(X^*) - fi(x)}{fi(X^*)}\right)^K ,$$

Where X* is the solution of the problem with a single objective. A comparison of the pros and cons indicates that the global criterion model can be applied to our context only in order to get a rough idea of a "good" solution.

ADVANTAGES	DISADVANTAGES
-- do not need additional information from the DM	-- without articulation of preference information
- DM not disturbed by analyst	- low confidence in solutions
-- easy to use with K = 1	-- many assumptions on DM's preferences implicitly involved
	-- choice of parameter K predetermines "optimal" solution, but value of K cannot be chosen in a theoretically satisfying manner, choice of K arbitrary
	-- for $K \neq 1$ problem becomes nonlinear

6.3 Goal Programming (GP)

GP is one of the approaches most often proposed to handle problems with multiple objectives. Recent surveys of the state of the art were provided by Kornbluth (1973) and Nijkamp and Spronk (1977). The approach has been applied to a large number of practical problems in very different fields ranging from manpower planning to environmental protection. GP minimizes a weighted combination of the deviations from a number of goals (target levels, aspiration levels) which are set by the decision maker. This aspect distinguishes GP from the theory of the displaced ideal (Zeleny, 1976).

The large number of applications can be explained by the flexibility of the method and by its correspondence to recent results of the behavioral theory. Versions of GP have been elaborated for:

-- interactive GP (Dyer, 1972; following the classification of Larichev and Polyakov, 1980, Dyer's method is pseudo-structured and the information required is difficult to obtain; Spronk, 1979).

-- integer multiple objective GP (Lee, 1977a,b).

-- nonlinear GP (Monarchi et al, 1976).

Some references provide programs for solving MODM problems using GP. Multiple goal programming is computationally not very sophisticated; many problems can be reduced to linear programming ones for which standard routines exist. Many specific problems can be handled within the framework of GP, modifying the basic method. One can, for instance, weight the deviations and in this way reflect the relative importance of negative or positive deviations.

Drawbacks of GP (large amounts of a priori information concerning target levels, weights, etc.) can be avoided by interactive approaches. The application of GP to the problem formulated in Section 3.1 will be discussed in Section 7.

6.4 Step Method

The step method is a structured interactive procedure (with implicit trade-offs between several objectives) for linear programming problems. Thus, it can be easily combined with the first formulation of our basic model (see Section 7).

An evaluation of some existing interactive procedures made by Wallenius (1975) indicates that the method STEM developed by Benayoun, de Montgolfier, Tergny and Larichev (1970) compares favorably with the other procedures reported in the literature; most of them were unstructured or pseudo-structured.

STEM starts with the construction of a pay-off table which can be realised with the already existing computer programming for our basic model (first formulation, see Section 7). Thus and ideal solution is calculated. STEM determines the "best compromise" in a number of cycles consisting of a calculation and a decision making phase. In the calculation phase a feasible solution is found which is nearest in a specific sense to the ideal solution. In the decision making phase the decision maker compares the solution obtained during the last calculation phase with the ideal one and indicates the objectives which can be relaxed as well as the amount of relaxation in order to improve unsatisfactory objectives. All questions are asked in the specific language of the decision maker who can think in terms of goal achievement and not in terms of explicit trade-offs between several objectives. The number of cycles is fewer than the number of objective functions (see Benayoun et al, 1971a). The authors of STEM suggested versions of their method for the following three cases:

(a) weights reflecting relative importance of the objectives are known

(b) objectives can be ranked in accordance with their importance for the decision maker

(c) no information is available about the ranking of the chosen objectives.

For our case study version (b) applies. The modifications of the basic STEM algorithm is described in Benayoun et al (1971b).

STEM has been successfully applied to a number of real life problems and modified for specific purposes (Dinkelbach and Isermann, 1980; Hashimoto, 1980) underlining in this way the intrinsic value and flexibility of this method. STEM should be attractive for decision makers, because the procedure does not rely on trade-off functions and involves weighting factors only when their assignment is not difficult.

6.5 Decision Analysis (DA)

6.5.1 Characterization of DA

The decision analysis group at the Stanford Research Institute characterises decision analysis as follows (Howard and Matheson, 1976): It is a normative discipline concerned with the practice of rational decision making.

What is the basis for the great pretensions of the decision analysts who assert that "decision analysis is the most powerful tool yet discovered for ensuring the quality of the decision making process " (Matheson and Howard, 1968, in: Howard and Matheson, 1976)?

Decision analysis (DA) was specially developed for complex, uncertain, dynamic situations with long term effects and relies upon Bayesian statistics, subjective expected utility, multi-attribute utility theory and several methods developed by operations research. The new theory was successfully applied to a number of practical problems. Some of the case studies are reported in Matheson and Howard (1976), and in Operations Research (Vol. 28, 1980, No.1). Advantages of DA are the involvement of the decision maker in the problem solving process and consideration of subjective knowledge, time preference and risk attitude of the decision maker.

First optimism of decision analysts that almost all decision making problems can be handled by decision analysis was replaced by more realistic statements about the value of this new decision problem solving technology (see, for instance, Howard, 1980). From our standpoint DA can be most useful in the field of economy but is less applicable to problems with strong or dominating social components. Decision analysts admit that some theoretical questions have not been solved yet by DA. Matheson mentioned some gaps in the theory in Matheson and Howard (1976). But these "white spots" do not necessarily narrow the practical applicability of this new theory.

First tutorials in DA pointed out that DA is a normative rather than a descriptive theory. The extensive application work of the last few years has shown that a normative theory must be based on a satisfying description of the real decision making process.

Decision trees are a very useful and common tool which reflect on a time scale alternative options arising from decisions and chance events. We characterised them in section 5.3 of this paper in their application to the selection andevaluation of innovation projects. Here we will report some recent research efforts directed to the application of decision trees.

6.5.2 Recent research work on decision trees

A lot of research work has been done on facilitating the application of decision trees to innovation management. This work is aimed at the development of efficient methods for analysing decision trees (Moskowitz, 1971; Marien and Jagetia, 1972), at synthesizing several approaches including decision trees (Chapman 1979), the development of new methods for extracting subjective probabilities from the decision maker (Yager, 1977) and the foundation of fuzzy decision analysis (Watson, et al 1979; Chang and Pavlidis, 1977).

On the whole these new efforts soften several disadvantages of decision analysis and decision trees and make them more useful. Some of these results were obtained recently, did not overstep the stage of theoretical investigations or of laboratory tests and are far from being applicable in business (this refers, to a certain degree, to the combination of fuzzy-set theory and decision analysis suggested in Watson et al, 1979).

Finally, these developments rely on equipment which is not yet available even in large firms (for instance, color video projectors, see Levin, 1978). Opportunities for an effective application of such equipment must be secured for its broader usage.

Chapman (1979) demonstrated the flexibility of decision tree analysis combining it with key characteristics of network approaches. His methodology "reflects a strong belief in approaches which are interactive, nested, and intuitively driven, integrating model selection and solution in modular fashion, with diagrams and computations emphasising and robustness rather than precision and generality."

In their combination of fuzzy-sets theory and decision analysis Watson et al (1979) allow for fuzziness on the probabilities and utilities. The authors stress the difference between imprecision of the input data and the uncertainty of the future state of the world. These qualities are modeled in a different way using fuzzy-set theory and probability theory respectively. Critics attack decision analysis for its imprecision of the data provided by the decision maker ("garbage in-garbage out").

This problem cannot be solved only by a variable-by-variable sensitivity analysis, as it is normally performed, because in reality variables may change in combination. Many decision makers are put off by the necessity to provide the data in numerical form. Watson, et al (1979) show that this requirement can be diminished or even replaced. It can be expected that decision makers will provide their assessments on values, utilities and probabilities in verbal form in the future. The authors mention that they could not offer an all-purpose tool, but the general direction of improving decision analysis is outlined. The potential usefulness of the suggested combination of fuzzy sets and decision analysis is obvious.

At Stanford University (California, USA) a program package (Tuan, P.L.) was developed for on-line network picture processing. Interactive computer graphics are used to process network pictures including decision trees. With these interactive computer graphics one can compose, decompose, simplify, transform, merge and regenerate network pictures like decision trees. The purpose of this system is the acceleration of the convergence in man-computer experiments.

Some of our initial thoughts about the structure of a man-machine system (see section 7 of this paper) for the selection of innovation projects which is based on decision trees are similar to the study reported. We will use some suggestions to improve our system.

Systems for picture processing will considerably improve the overall capability of the whole system for the selection of projects because they shorten the tedious and lengthy work of drawing decision trees for all projects under consideration.

Similar efforts are reported by Lewis (1975), Thompson and Kirschner (1978), and by Leal and Pearl (1977, 1976). Lewis' interactive system for editing tree structures allows to insert, delete, search and to display any branch of a given tree structure. Leal and Pearl described an interactive computer program which has been designed and implemented to elicit decision trees from decision makers. The automation of the tedious process of eliciting decision trees in an English-like conversational mode greatly facilitates the distribution of decision analysis techniques.

Leal and Pearl's approach does not depend on the domain of application. All input data provided by the user is immediately mapped into one of the data types (events, actions, likelihood relations, etc.). One of the biggest disadvantages of the manual eliciting of decision trees is the danger of spending much time on details of the tree which are not relevant to the final solution of the problem. Leal and Pearl use an efficient tree expansion method directing the effort to the most critical tip node, which is defined as the node that is most likely to change the currently best first step solution. This tree expansion method is based on a senstivity analysis algorithm and the analogy between decision tree elicitation and heuristic search on game trees which was first mentioned by Leal and Pearl.

A generalization of these efforts is provided by Levin, et al (1978) who developed a system for interactive computer aiding of group decision making based on decision trees. Decision trees are constructed using value and probability inputs from all group members. The system does not assume familiarity of the decision makers with decision analysis and computer programming. Systems developed become more and more friendly to users. The way becomes clearer for the realization of the forecast (see Matheson and Howard, 1968): "Soon the logical structure of any decision analysis might be assembled from standard components". We cannot overlook the discrepancy between the inspiring opportunities opened by researchers and the actual application of those systems in daily decision making. But the general direction of computerised decision support systems based on decision analysis seems to be clearly outlined.

Decision analysis is becoming a new industrial branch. First firms were already founded, for instance, Decisions and Design Inc. USA.

6.5.3 Assignment of Probabilities

The assignment of probabilities to the chance outcomes of the chance nodes is involved in the expected utility concept. Many theoretical investigations on decision analysis assume that these probabilities are either known or easy to obtain. Applications of the theory to real world decision situations have indicated that this is not true. In the early 70s psychologists investigated the capability of decision makers to process probabilistic information (Tversky and Kahneman, 1975; Kaplan and Schwartz, 1975; Slovic, Fischhoff and Lichtenstein, 1977a,b). The results were disenchanting. Decision makers employed several simplifying heuristics and rules in situations with uncertainty leading to considerable biases which question the use of probability assessments made in this way.

Tversky and Kahneman (1975) found that people tend to reduce the overall complexity of an assessment task to a set of simple tasks using some heuristic principles, which may under specific circumstances result in questionable decisions because of systematic errors in the assessment:

-- subjective assessment of probability is based on data of limited validity; scientists seriously underestimate the error and unreliability inherent in small samples of data (Tversky and Kahneman, 1971); summarizing other studies, Slovic et al (1977) concluded that scientists:

  (a) had unreasonably high expectations about the replicability of results from a single sample;
  (b) had undue confidence in early results from a few subjects;

(c) gambled their research hypotheses on small samples without realizing the extremely high odds against detecting the effects being studied;

(d) rarely attributed any unexpected results to sampling variability because they found a causal explanation for every observed effect;

(e) people seem to rely almost exclusively on specific information and neglect prior probabilities;

(a)-(e) is called bias due to representativeness.

-- bias due to availability: there are situations in which people assess the frequency of a class or the probability of an event by the ease with which instances or occurrences can be brought to mind (Tversky and Kahneman, 1975);

-- bias due to anchoring: in many situations people start to estimate the probability of an event with a natural starting point (anchor) which is then adjusted; these adjustments are often insufficient.

Psychologists found a lot of other biases due to simplifying heuristics. The problem arises whether these results question decision analysis?

(a) The observed behavior of people in assessment tasks under uncertainty was found to be valid for tests which were specially prepared in laboratories. The hypotheses concluded from these experiments are vaguely formulated: "in many situations", "there are situations in which people...", "often" and so on. Slovic et al (1977) argue that "much evidence suggests that the laboratory results generalize. Cognitive limitations appear to pervade a wide variety of tasks in which intelligent individuals serve as decision makers..." (For details of the discussion about this topic see, Slovic et al 1977). There is no pretension of the psychologists to cover all decision situations and all decision makers. No doubt these psychological investigations are important for the understanding of people's cognitive processes; but we believe that it is to early to condemn decision analysis. Some other considerations support this belief.

(b) The usage of probability estimates which are biased to a certain degree will not have catastrophic impacts on the results obtained with the approach proposed in this paper. A sensitivity analysis will reveal the importance of a particular estimate for the solution. Several procedures can be applied to calibrate probability assessments (see, for instance, Spetzler and Staël von Holstein, 1972; Lichtenstein, Fischhoff and Phillips, 1977).

(c) We have to consider the problem of probability assignments to future events in a more general framework: the evaluation process as a whole, including also assignment of value or utilities to certain consequences of our activities. The utility aspect is of the same importance with respect to societal decision making as the probability aspect (Jungermann, 1977).

(e) Tackling problems of high complexity (and decision making on innovation projects is doubtless of this kind) the analyst and the decision maker must have the courage to simplify.

The criticism of decision analysis centers around its roots: the expected utility concept, the assignment of probabilities and the multiattribute utility concept.

6.5.4 Expected utility concept

Expected utility, as mentioned above, is one of the concepts decision analysis relies upon. It assumes that decisions are taken in dependence of the product of utility and the probability of the occurence of a certain option. Some decision makers and decision scientists argue that risky choice is not determined by maximization of the expected utility. An alternative theory was suggested by Coombs (1975), but it has never been implemented or used.

One cannot say definitely whether expected utility is a good or a bad basis for decision making under circumstances of uncertainty. Following Larichev's classification of the methods for multiattribute decision making (see Figure 12) models using expected utility as a criterion belong to the class of direct methods. Defining or postulating the form of the criterion (expected utility) the decision analyst gets rid of all problems. But the question arises whether this postulate is justified or not.

Kahneman and Tversky reported unambiguous violations of the subjectively expected utility theory (see Bell, Keeney and Raiffa, 1977). They observed that, people tend to value consequences known with certainty more than uncertain consequences. Kahneman and Tversky called this violation the certainty effect. Another one is the reference effect. People seem to evaluate alternative options relative to a reference point determined either by expectations about the future development or by status quo. This reference effect is one of the main arguments of the proponents of the reference point approach which is being developed by Wierzbicki and others (see Wierzbicki, 1979, 1980a,b). These two effects have to be considered serious problems for the normative theory and its application (see Slovic et al, 1977). Proponents of the expected utility concept could argue that one could elicit the "uncertainty preference" from the decision maker like risk or time preference and formally include it into the analysis.

6.5.5 Methods based on MAUT

MAUT methods are intensively discussed in the scientific literature. Their applicability to real life problems was, for instance, critically reviewed by Humphreys (1977), Fischer (1975), von Winterfeldt and Fischer (1975), Humphreys and Wisudha (1980), Larichev (1979). Project attributes important for R&D project selection are discussed in Schwartz and Vertinsky (1976b). Their investigations focused upon the following attributes:

- cost of the project relative to total R&D budget
- the payback period
- the probability of technical and commercial success
- market share impact
- expected rate of return
- availability of government partial funding for the project.

We will check the value of MAUT for our case study and weight strengths against weaknesses. MAUT is a strong and sophisticated mathematical theory (see Fishburn, 1970). Humphreys defines MAUT as a part of a multi-level decomposition-recomposition procedure. From his viewpoint three levels of decomposition exists: On level 0 (no decomposition) the decision maker's behavior is conceptualized in terms of a sequence of identifiable acts. Decomposition to the level 1 (choice alternatives) can be considered as the construction of a decision tree of the choice problem including assignments of utilities to all end points of the branches of the tree (decomposition to level 2 (multiattribute outcomes)). Thus our basic model fits well into the concept of MAUT. The main concern of MAUT is the decomposition of multiattribute utility functions to a set of simple single attribute utility functions which can really be assessed. For this purpose a set of axioms is applied determining the admissable degree of decomposition. The systems of axioms are reported elsewhere (Fischburn and Keeney, 1974).

An analysis within the framework of MAUT for our case study includes the steps indicated in Figure 13. The test of the validity of the axioms is very complicated, in practical applications, especially if the number of objectives is greater than 2. In our case three objectives are indispensable. An incomplete test of the axioms (with a limited number of examples) seems to be practically feasible. Intensive field studies of psychologists have shown that the axioms cannot pretend to be of general applicability (Allais, 1953; Slovic and Tversky ; von Winterfeldt and Fischer, 1975). Often disaggregation of the general utility function is performed regardless of violations of the axioms. Simple additive models are most popular. Several investigations indicate that minor violations did not have a great impact on the quality of the problem solutions because of the robustness of the simple additive model (Fischer, 1972).

Humphreys (1977) discusses options to be taken in applications if assumptions do not hold and states that most violations do not seem to be of critical importance for the validity of the solutions obtained (except for the sure thing assumption which is discussed in greater detail in Tversky, 1974).

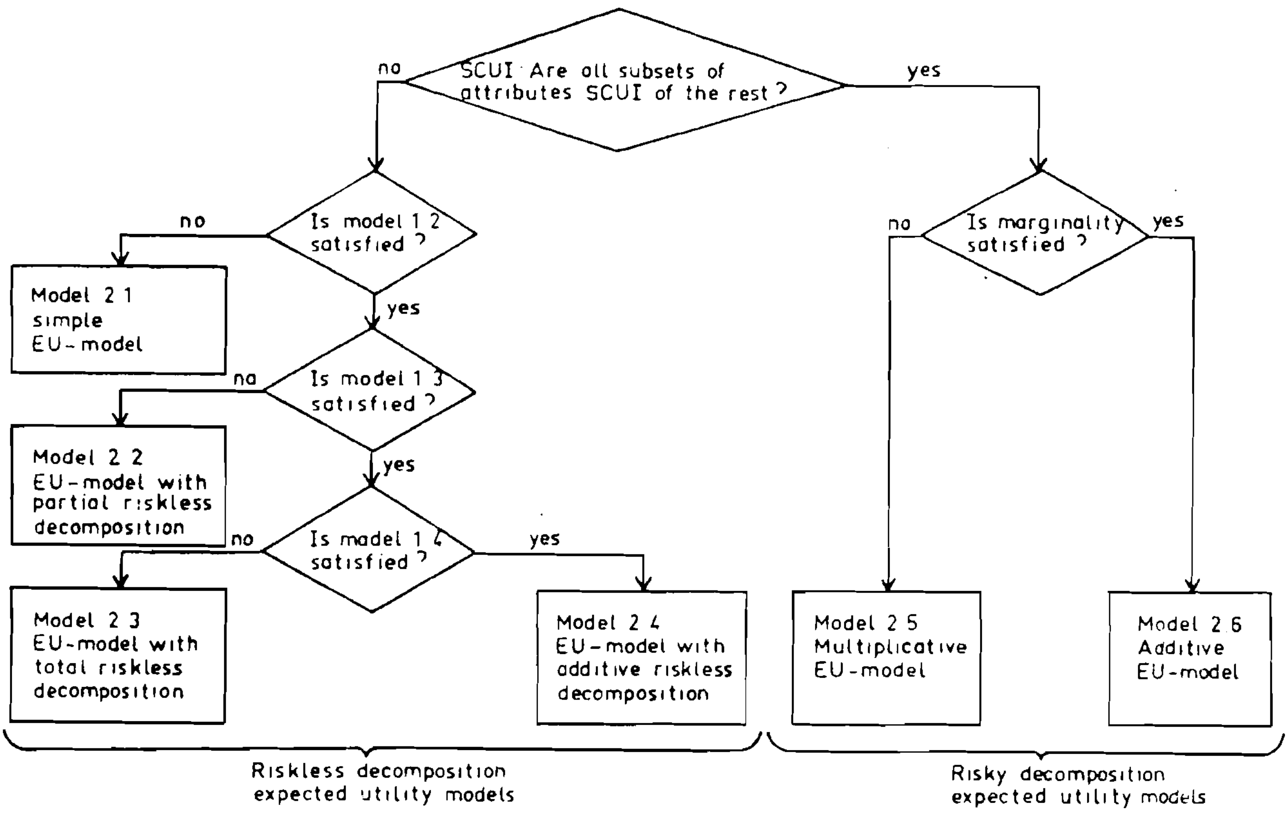


Figure 13 Tests of models for the time-invariant risky multi-
attribute choice situation
(Source: von Winterfeldt and Fischer, 1975).

Sometimes the question arises whether it is sensible to spend considerable effort needed to test the axioms, because it seems reasonable to postulate an additive or multiplicative form of the overall utility function. "Consequently, except in very simple laboratory experiments, validation of MAUT makes no sense at all". (Bauer and Wegener, 1977). A test of the axioms is intended to prevent the application of specific disaggregation rules when they are obviously wrong. Recent applications of MAUT put emphasis not on formal axiomatic considerations but on the specific task environment the decision maker is faced with. In this way MAUT becomes more attractive for real world applications.

Let us summarize the mose important drawbacks of MAUT:

-- MAUT assumes complete and definite information about the decision maker's preference to be available at the beginning of the decision making process (the opposite assumption seems to be true in most practical situations, see Dinkelbach and Isermann, 1980; Hwang, 1980).

-- MAUT is based on rather strong assumptions concerning rational behavior (see Keen and Morton, 1978) of economic man; some investigations (March and Simon, 1958; Wierzbicki, 1980) support the hypothesis that everyday decisions are not made by maximization of utility functions but rather by establishing certain reference levels.

-- The most important concern of MAUT are not real life decision making problems but formal considerations centered around the form of the disaggregation rule for the overall utility function.

-- MAUT is suited first of all for repetitive choice situations (Wierzbicki, 1979; Larichev, 1979) (our problem is located between repetitive and unique choice situations). But there are also applications to unique decision situations (see Bell, Keeney and Raiffa, 1977; Keeney and Raiffa, 1976).

-- It is extremely difficult or almost impossible to test the axioms

- o because of lack of efficient test procedures
- o tests impossible for all data
- o questions for validity tests impossible to answer, DM is unable to make the necessary judgments.

-- If axioms are violated (in our case this refers first of all to the sure thing principle and to the marginality assumption, see Slovic and Tversky, 1974), then decision theory in the form of MAUT cannot assist our analysis, and an alternative approach has to be exploited.

-- The number of applications of MAUT to risky multiattribute decision making is very small (von Winterfeldt and Fischer, 1975, reported only two cases) in most cases additive, riskless, time invariant models are applied.

-- The assessment procedures for utilities are clumsy, complicated, difficult to understand, time-consuming, do not allow for mistakes and require answers to imaginary questions (see von Winterfeldt,). Two case studies may serve as an example for rather dubious questions requiring an answer from the "experts". Keeney and Raiffa (1976, p.452) asked "what amount of safety X_4 was such that (X_4:2500) was indifferent to (1:1,500,000). That is, X_4 people seriously injured or killed given an accident and 2500 people subjected to high noise levels is indifferent to one person seriously injured or killed and 1,500,000 subjective to a high noise level". (The answer was 300!). Keeney (1975) studied the alternatives for producing electrical energy in Wisconsin. Fatalities due to working in coal mines, nuclear power plant disasters, etc., and the loss of land were a few of the attributes for evaluating energy pricing. The expert was asked: "How many people on a first guess would you be willing to give up to be indifferent to these 2000 acres?" Fortunately, not all applications require confusing questions like these.

-- No general recommendations can be given which assessment procedure for utilities is the best one.

-- Basic reference lottery tickets are the common tool for the assessment of expected utility functions necessary for our case study.

Bauer and Wegener (1977) explain the discrepancy between the sophisticated and well-developed body of MAUT and the small number of real world applications with "limitations concerning the overall complexity that can be processed by it". Considering multiattributivity, uncertainty, and time-variability as the main factors determing the complexity of a given decision situation, they argue that "further decomposition of one ofthe three dimensions... has to be paid for with higher aggregation in the two other dimensions, unless simultaneously progress is made on the instrumental side of the modeling techniques, e.g., by introducing choice heuristics or interactive computing assistant".

In the face of the weaknesses of MAUT summarized above it becomes difficult to justify its application to our case study.

6.6 Reference Point Approach (RPA)

The following discussion is based on Wierzbicki (1979a,b, 1980), Kallio et al (1980) and Hashimoto (1980). The RPA is a relatively new approach avoiding many of the drawbacks of the more traditional approaches to MODM. Wierzbicki (1979b) advocates the hypothesis that everyday decisions are not made by maximizing utility functions but rather by establishing certain reference levels for objectives and trying to satisfy them. This hypothesis seems to be valid for the problem formulated in section 3.1 where decisions to be taken have features both of repetitive and unique decision situations and where the preferences are conscious but variable. At present RPA is not fully developed. The problems of an appropriate reflection of uncertainty have still to be investigated. Successful implementation of RPA were reported by Hashimoto (1980) and Kindler et al (1980). A package of programs has been elaborated for automating RPA.

The main advantage of RPA in comparison with the traditional MODM methods is that the DM can specify target levels which are used to define a Pareto optimal solution which is as close as possible in a specific sense to the reference point. The DM can think in terms of goals instead of in terms of utilities and preferences which is quite unnatural in practical decision making as was mentioned by Zeleny (1980). RPA improves a crucial aspect of interactive MODM methods--the for in which additional information from the DM is provided (see Larichev and Polyakov, 1980).

A particularity of Wierzbicki's approach is that any reference point--attainable or not--can be used. Thus, the RPA is more general than most of the previous approaches which used reference points of a certain kind. Kallio et al (1980) discussed forms of the penalty scalarizing function resulting in linear programming problems. RPA can be combined with our approach developed in Section 7.

7. DEVELOPMENT OF THE MODEL FOR THE PRESENT CASE STUDY

7.1 Some Introductory Remarks

In this chapter we will discuss some ideas related to the problem of how to develop a decision support system for management decisions, which projects for innovation should be adopted and how much to spend on them. This development process will be performed step by step. We will first describe the basic approach we intend to implement and some of its versions suited for different circumstances which might occur in the firm under consideration.

At the present stage of our investigations it is too early to speculate about the final construction of the DSS. A DSS will be the long-term goal of our work. Extending the basic approach we will rely upon the findings of psychologists, management scientists and specialists in the field of DSS and on the experience of the implementation of R&D project selection models. The development process of the intended DSS will extend over some years. At each stage we will have to decide in cooperation with the decision makers of the firm (who welcome our efforts directed towards a higher objectivity of the decisions) whether it could be worthwhile elaborating the basic approach. In this decision we cannot simply calculate the efficiency of a further sophistication because the aim of a DSS is not efficiency but effectiveness.

Caution in the development process of the DSS is recommended for several reasons:

- only a few successful applications of R&D project selection models are known;
- only few approaches suggested recently have been tested in a wide range of practical situations (this refers to multiple objective decision making under uncertainty, fuzzy decision analysis, etc., as well).

The orientation towards decision analysis that we adopt can be explained by the flexibility of this approach and the great number of reported successful applications to real world problems, including the management of R&D.

The further progress of our research project will also depend on the success of our efforts to create an atmosphere of growing support from the decision makers and from specialists in a number of disciplines like, for instance, MODM, fuzzy sets theory, decision analysis, computer techniques. These factors are considered to be decisive for the eventual success of our studies (see Alter, 1980).

A basic principle of the development of our DSS is the modular principle. All techniques applied should be jointly compatible so that the analyst (or decision maker) can choose how to combine them. This principle guarantees the adaptation of the model to new requirements or to new findings in the rapidly progressing field of DSS. We should point out once more that we are still at the stage of searching for the "best" approach for our problem. This is the main reason for our efforts of testing a number of them, briefly discussed in Section 6. In practical applications hybrid models have often proved successful (see Hogarth, 1974; Chapman, 1979; Bunn, 1978).

7.2 Interactive Mode of Operation

Before we discuss the basic model and several versions we must find an answer to the following question: Why is an interactive manner of operation necessary for our case study?

In a complex situation like the evaluation and selection of innovation projects with multiple objectives, uncertainty and long-lasting effects on the company as a whole, a decision maker is often not able to articulate his preferences well enough to construct a utility function. The first presentation of the problem the decision maker is faced with, will be, in most cases, very vague and will have to be corrected within a feedback loop. This is the main reason requiring the decision maker to be involved in the problem formulation, solution and evaluation of the results. The decision-maker may wish to change some of the data the decision tree is based on as, for instance, the resource requirements of a certain project path in a particular time period, the benefits to be expected if a particular project is realized, the probability of certain chance nodes and so on, and assess the impact of the changes on the final solution. The changes may affect even whole branches of the tree which can be deleted or inserted.

The generation of a feasible set of alternatives is in some cases more important than the solution itself because it predetermines the final choice. Our approach is intended to be process-oriented and should allow for any changes the decision maker is willing to undertake. Figure 14 shows the principal structure of one of the model versions (it will be discussed in the next section 7.4). Many models for project selection have not been adopted because the decision maker did not feel that their real preferences were reflected adequately.

An interactive procedure will greatly increase the decision maker's confidence. "Human decision making paradigm must be amplified rather than reduced, understood rather than ignored, respected rather than degraded" (Zeleny, 1980). Interactive decision making is at present the best way to meet this demand.

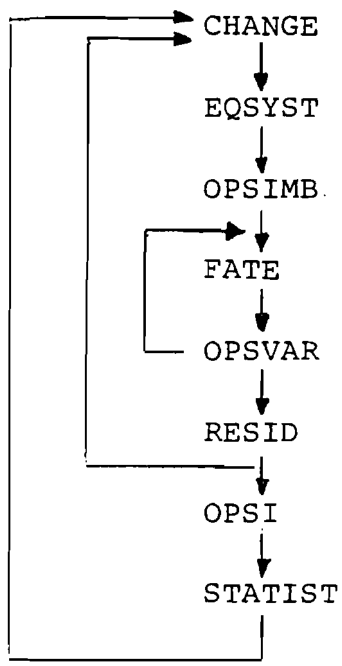


Figure 14 Structure of the Computer Programme for the Second Problem Formulation.

The main idea of interactive decision making is the joint soliciting of the decision maker's preference structure and the investigation of the feasible set of alternatives for the eventual determination of an "optimal" solution. The most important problem in the assessment of an interactive procedure is the ability of the decision maker to answer the questions asked by the algorithm. One cannot expect questions to be answered which are difficult for the decision maker even without a computer.

A classification of interactive procedures based on the key question--the distribution of the work to be done between the decision maker and the machine--is provided by Larichev and Polyakov (1980). They distinguish between unstructured, pseudo-structured and structured procedures which differ in the degree of the decision maker's involvement in the process of finding a solution. In this paper we will consider only structured procedures because of their relative simplicity. Structured procedures reflect results of psychological investigations on human capabilities in comparing multiattributed alternatives and start from the finding that these capabilities are very limited. Hence, interactive procedures should ask simple questions.

7.3 Basic Model and Versions

The basic model can be formulated in several versions depending on the problem size which is determined by:

-- the number of projects under consideration

-- the structure of the decision trees (number of decision and chance nodes and corresponding branches)

-- the number of time periods

-- the number of resource types formally included.

Given that the problem size is not too large the evaluation and selection problem takes the form of a stochastic linear programming problem in which the uncertainties about the future are incorporated in the objective function.

The decision variables are designated by $x_{ij_tf_t}$. This is the path of j of a given project i in time period t under the assumption that the future state of the world f has occurred in time period t. The future state of the world is determined by the chance outcomes of chance nodes up to time period t (for further details see, for instance, Gear and Lockett, 1973). The constraints of this model version guarantee that not more than one project path of each project will be selected and ensure that resource availabilities are not exceeded in all time periods and that complete project paths are either adopted or rejected. Given that the value of the endpoints can be expressed in monetary terms, the objective function can be formulated as the maximization of the overall expected value of the sum of terminal values of the projects. Similar expressions can be found for the other two objectives mentioned in section 3.2. Other constraints arising from peculiarities of the firm of the present case study can be easily included.

The first version of our model formulation takes into account the order in which decisions and uncertainties arise on each project over time. One gets the solutions for all possible future states of the world in one computer run. Parallel approaches in R&D can be modeled. By defining the nodes of the decision tree in an appropriate manner one can take into account uncertainties in resource requirements, project duration, project outcomes. The results of the calculations indicate how to allocate the available resources (the questions includes two aspects--which projects to choose and how much to spend on them) in time period 1 in order to be on the optimal path in the future. If the number of decision variables is large, then difficulties may arise in the analysis of the solutions.

The first problem formulation is, from our viewpoint, well suited for interactive multiple objective decision making and can be combined easily with approaches like STEM or with the reference point approach (see Wierzbicki, 1979a, b; Wierzbicki, 1980; Kallio, et al, 1980), because all uncertainties involved in the decision trees are represented in the objective function. In the interactive problem solution the decision maker can manipulate only in the objective space.

We hope, that because of the relatively small number of projects in our case study we need not exceed the limits of solvability with the existing standard packages. Moreover, it is possible to reduce the problem size which is increased, first of all, by the number of chance nodes in the decision trees. The necessary theory is provided by Lockett, et al (1980) for the single-objective case.

Finally, one could be satisfied with a good, feasible solution with upper and lower bounds on the expected value of the optimal solution instead of strong optimization which has no real sense (see Lockett, et al, 1980).

The alternative approach, combining linear programming with simulation and heuristic analysis of the solutions will be applied if all these possibilities of reducing the problem size are not sufficient. In this case it seems to be best to apply ideas of MAUT in order to determine the trade-offs between the different objectives, and to assess an aggregated value for each of the alternatives. The problems in the assessment of the multiattribute utility function are weakened by the small number of objectives. In this case we will rely on approaches like those developed by Keeney and Sicherman (1975).

With an increasing size of the linear programming problem corresponding to the decision trees of the innovation projects it becomes more and more difficult to solve the problem with existing standard solution packages, even when a branch-and-bound method is applied. The decision maker can also get lost among the very large number of printed decision variables. These are the main reasons for the development of an alternative approach for the representation of the same problem. It combines linear programming, simulation and heuristic interpretation of the results. Each project path of a given innovation project is represented by one decision variable. The constraints of the model ensure that resource availabilities are not exceeded in all time periods and for all kinds of resources.

In the second problem formulation the chance nodes of the decision trees are repeatedly sampled. In this way the problem is reduced to a deterministic linear programming one. This simulation results in some additional constraints. Their number corresponds to the number of project paths in which chance nodes are incorporated. The constraints differ only in the right-hand sides of the linear inequalities. A set of 0 or 1 is generated in each simulation run. A 1 means that the corresponding project path is being considered in this run. This approach was first reported in Lockett and Freeman (1970). The application of Monte Carlo techniques is also proposed in Allen and Johnson (1971). We developed a computer program which generates, for a set of given decision trees, the corresponding linear programming problem with a fixed matrix of coefficients and a number of right-hand sides. The solutions can be analysed using statistical means and variances for the cases that the decision variable is element of the basis or not (for details see, for instance, Lockett and Gear, 1973).

The presentation of results of the model runs in this way is, from our viewpoint, very convenient for the decision maker. The proposed approach can handle a large number of innovation projects with complicated structures and highly disaggregated resources and time periods. A weakness of the second approach is the problem of final choice. It is also not suited for an interactive manner of operation, but can be used as a convenient starting point for an analysis with the approach discussed above combined with man-machine dialogue. We think that a combination of both approaches is the best way to arrive at a more realistic picture of the whole decision process on innovation projects.

The basic model discussed here is linear. Many detailed studies have indicated that linear models:

-- are a good approximation of real R&D situations (Allen and Johnson, 1971; Bell and Read, 1970),

-- are easy to handle,

-- are easy to understand for decision makers,

-- can easily be extended to multiobjective decision making problems (the theory and computer programs for multi-objective linear problems are discussed intensively in the literature, see Zeleny (1974), Evans and Steuer (1973)). Nonlinear problem formulations do not add to reality and often cannot be solved by standard computerized solution techniques.

7.4 Stage of the Work

Working on our case study we programmed the second problem formulation first. The reasons were of practical nature. The principal structure of the program which was written in PL/1 is shown in Figure 14.

The structure of the computer program shown in Figure 14 also applies to the first problem formulation, the only difference being that the subprograms FATE, OPSVAR, STATIST are unnecessary. Subprogram CHANGE has the following functions:

-- store all input data in the form of lists (see Knuth, 1973),

-- organize the dialogue between machine and decision maker

-- make possible all changes the decision maker is willing to undertake (changes of outcomes, resource requirements, resource availabilities, probabilities, insertion or deletion of branches, etc.).

Having implemented a working version of the whole complex of programs, most effort will be concentrated on the refinement of CHANGE. Some possible ways of doing that were discussed in section 6.5.2. The main aim will be the automation of the process of eliciting decision trees in a language close to conversational as it was described by Leal and Pearl (1976).

EQSYST is a subprogram generating the matrix of coefficients of the linear programming problem corresponding to the elicited decision trees. By running the subprogram OPSIMB this matrix is stored on a tape in a form necessary for the standard program which solves linear programming problems. For each coefficient matrix, FATE generates a set of right-hand-sides of the linear programming problem which are stored on the tape by subprogram OPSVAR. RESID constructs all remaining constraints of the linear programming problem, which is then ready for solving by the standard program OPSI. What follows then is a statistical analysis of the simulation runs with STATIST. Having analyzed the solutions, the decision maker can return to CHANGE and adjust the input data. All calculations are performed in the computer center of the University of Economic Sciences in Berlin on computers of the ESER type.

7.5 Application of Goal Programming

For work on our research project we need a schedule for its continuation, based on the discussion of the different approaches for MODM in section 6 of this paper and within the bounds of possibility of our firm.

In view of discussions of new approaches in the scientific literature (see, for instance, discussions on fuzzy decision analysis in Freeling, 1980), showing that their implementation sometimes creates more problems than it can solve, we rely on approaches widely adopted and tested. What will be useful for almost all approaches (goal programming, STEM, global criterion method) is the optimization of the problem for each benefit area separately. This is possible with the programs already written. The maxima in the different benefit areas can be used, for instance, in goal programming as the target value, the decision maker has to determine. Some recent papers (see Muhlemann, et al, 1978; Lockett, el al, 1980; Harrington and Fischer, 1980) have shown the principle possibility to apply goal programming to the problem of R&D project evaluation and selection. Some simple examples illustrated the modifications necessary to apply the basic approach we use (section 7.3). Several forms of the objective function were discussed ranging from the maximum weighted expected portfolio deviation from a set of goals to the maximum of the minimum weighted portfolio deviation from a set of goals. In the second case the assignment of probabilities to the chance nodes is unnecessary. Our task consists in the realization of the theoretical findings in the present case study. In this work we have to avoid some simplifications in the quoted papers; this refers, for instance, to the assumption that the benefits in the different areas can be summed up.

7.6 Application of STEM

In this section we will discuss the application of STEM to our problem and the changes necessary in the program structure outlined in Figure 14. Our first problem formulation corresponds entirely to the problem considered in Benayoun, et al (1971a). The basic STEM procedure is valid for the case of known weights of the different objectives. Our program (Figure 14) can be exploited for the optimization with respect to each of the three particular objectives mentioned in section 3.2 Only one step must be added in order to implement STEM: the optimization with respect to the total objective which is the weighted sum of the particular objective functions. If the optimization with respect to the "total objective" does not provide a satisfactory solution, an additional constraint is introduced defining the minimum attainment levels to be met.

The procedure of seeking a compromise between the increase of a certain objective value and the reduction of others does not cause any important changes in the program shown in Figure 14. As was mentioned in section 6.4 STEM was developed in three versions for the following cases:

1. the weights of the objective functions are given
2. the relative importance of the objectives is known
3. no a priori information about the importance of the objectives is available.

Case 3 means that all possible systems of weights are equi-probable, which is not true for our problem. Case 1 is also unrealistic. Hence we have to deal with situation 2 which can be easily traced back to case 1 by considering the following statements to be valid.

The ratio 8:1 characterizes an overwhelming importance of one objective in comparison with another. Ratios 4:1, 2:1, 1:1 characterize significant greater importance, greater importance and equal importance respectively (see Benayoun, et al, 1971a). These assessments can be used to calculate weights which add up to 1. Many investigations have indicated that the correct value of the weights does not greatly influence the final result. This is the main argument for using these ratios of importance.

Though the case of known relative importance of the objectives is the most realistic, it is worthwhile imagining that no a priori information is available on the importance of the objectives. The results of the solution of this problem can shed light on the final decision to be taken. For this case, Benayoun et al (1971a) suggest the following method which is based on the idea that the optimization with respect to a particular objective j is identical to the optimization with respect to the total objective using the system of weights (0,0,...,0,1,0,...0), where 1 is component j of the vector.

We arrange the results of the optimization with each of the objectives in the form of a table, see Table 3. If the values of a certain column j of the matrix do not differ too much from the maximum value of column j which is attained on the principal diagonal, then a sufficiently large value with respect to objective j is achieved. Hence the weight of this objective in the system of weights can be taken as small. Benayoun, et al, suggests two methods for obtaining the weights of the objectives in the total objective function which differ in the degree of usage of the large amount of information contained in the matrix. In this way the case with a lack of information about the importance of the objectives is also traced back to the basic STEM procedure. The comparative simplicity of STEM is the reason for its wide acceptance.

Table 3

	c^1	c^2		...			c^m
c^1							
⋮							
c^m							

8. SUMMARY

In this working paper the first phase of an ongoing research project is presented. It is aimed at the development of an approach for the problem of allocation of resources between projects for innovation at a relatively early stage of their evolution.

This paper is a case study for the lighting industry of the GDR. The decision problem and the current trends of this particular industrial branch are characterized. We will go into the peculiarities of the lighting industry only to an extent, necessary for the understanding of the proposed methodology. Features of decisions on innovation projects are discussed, and their impact on the structure of our model is outlined.

Causes for the limited application of models proposed in the scientific literature are mentioned and suggestions are made to overcome some of the drawbacks of previous approaches. A first idea is presented about the structure of a decision support system for aiding management decisions on innovation projects.

Attempts to model the problem of choice of innovation projects and the problem of allocation of resources between adopted projects are fruitless without taking into account recent results of innovation theory. Some ways to do that are outlined in this paper.

Since none of the previously developed model approaches can handle the complexity of the decision situation we suggest to compare the results obtained by the application of different approaches which put emphasis on different aspects of the decision problem. Among them are decision analysis, the Step Method, the Reference Point Approach and others. We stress first of all decision analysis for several reasons: it is widely accepted and applied, several computer packages and procedures were developed and can be used for our special purpose. The research work already done is outlined and several future extensions are discussed.

Our basic model is based on decision trees which can be combined with approaches listed above. Two versions of the basic model are introduced and advantages and disadvantages are discussed.

The next step of our research work will concentrate on information gathering, programming and on the comparison of the results obtained. A decision support system will be developed step by step. Findings of this work will be reported in the next working paper.

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