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DECISION SUPPORT FOR INNOVATION MANAGEMENT: APPLICATION TO THE LIGHTING INDUSTRY

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FOREWORD

In today's turbulent economic environment, every decision affecting the development of industry necessarily carries an increased risk that the anticipated economic and social goals will not be achieved. The description of decision making does not always include the notion of risk. Sometimes the "volatility of cost factors" or changing economies of scale (innovation being the primary reason for the change) are held responsible for uncertainty about future development. These phenomena are also used to explain the decline in capital formation and in decisions to invest that we are currently witnessing.

The economic and decision sciences are trying to cope with this situation by devising more sophisticated methods and procedures for supporting decision making. This Research Report reviews some methods that are applicable to the analysis of innovation patterns, with the aim of basing the necessary decisions on more sound reasoning. The report then describes the application of some of these methods to innovation management in the lighting industry. It is hoped that their application will result in better decisions being made in the allocation of resources for innovation.

Tibor Vasko
Deputy Chairman
of the former
Management and Technology Area

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SUMMARY

Making decisions about resource allocation for future innovations is a challenging task in both planned and market economies. Not only can such decisions not be reversed without considerable loss of efficiency, but the decision maker generally faces a number of conflicting objectives. In this report the authors try to combine two disciplines that have been evolving independently for a long time: innovation theory and decision theory. A decision support system for managing innovations should reflect the multistage nature of the innovation process and should also be suited to multiobjective decision making. At the same time it is necessary to simplify the real situation for the decision maker in order to apply formal procedures.

A very promising scheme is the decision tree, though it has shortcomings. Application of decision trees is closely connected with the evaluation process. Almost all models for evaluating innovation projects operate with only one objective. However, discussions with decision makers in the lighting industry, which shows classic features of the innovation process, revealed the necessity to include at least three objectives in the evaluation. Therefore, the authors have made use of the possibilities of multiobjective decision making.

The decision problem in this work concerns the allocation of resources to innovation projects for the 1981–85 Five-Year Plan in the German Democratic Republic. At present the model for evaluating innovation projects is based upon linear programming and decision trees. It will be improved in close collaboration with decision makers, using the results of goal programming and other aspects of decision theory.

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1 INTRODUCTION

At one time the decisions that a firm made on research and development, investment, production, and marketing were relatively independent of one another. Nowadays, however, it is clear that every decision must take into account the whole process we call innovation. In addition, the changing and often turbulent conditions of the world and national markets have introduced more risk into decisions to reallocate resources among various innovative projects.

In this study we review the main approaches of decision theory to the evaluation and selection of projects and link them with innovation management. This is the first step of a research program that is being carried out at the Economic University of Berlin in the German Democratic Republic. The study was promoted by decision makers in the lighting industry of the GDR. An analysis of the decision-making process in this industry revealed the need for a decision support system. Our approach is thus tailored to the needs of this industry. Our ultimate goal is the development and implementation of a decision support system suitable for making decisions about innovation projects at the level of R&D management using a portfolio approach.

Since innovations are closely linked to national and international markets and resources, the interaction between governmental innovation policy and the technological policy of the individual firm is important. Although quality and consistency of corporate strategy are essential to the success of innovation, in practice corporate strategy does not provide complete insurance, because innovation is a complex phenomenon, touching all spheres of technological, economic, and social activity. We cannot hope to incorporate all of these interrelated activities into one quantitative decision support model. Moreover, it is questionable whether such an elaborate model would really assist the decision maker in arriving at better decisions. In our view it would be better to include certain crucial qualitative aspects, in the form of judgments concerning expected future states of the world.

The many factors that influence the development of innovation can generally be attributed to the innovator,the organization, and the environment. While no list of factors can be exhaustive, a brief survey, presented below, will help to indicate the advantages and shortcomings of the models proposed in the literature for aiding decision making on innovation projects, including our own approach (Haustein *et al.* 1981).

I. Innovator
    a. Input, output
        a1. Input-related factors: necessary quantities and qualities for production
        a2. Output-related factors: knowledge and utilization of properties and possible applications of technique
    b. Interaction of innovators
        b1. Interplay of functional roles that are necessary to accomplish innovative activities
        b2. Characteristics of innovators in these roles

- II. Organization
  - c. Resources
    - c1. Material resources
    - c2. Human resources
    - c3. Information
    - c4. Capacity
    - c5. Innovative potential
  - d. Organizational dimensions
    - d1. Relationships with the environment
    - d2. Internal dimensions
  - e. Organizational measures
    - e1. Planning
    - e2. Control

- III. Environment
  - f. Resources
    - f1. Natural resources
    - f2. Human resources
  - g. Competitive situation: time factor
  - h. National needs and goals
  - i. Demand

Each factor influences innovative activities in a specific way, depending on the circumstances; no general pattern of influence can be found. The degree of influence also changes over time, depending on the stage of the particular innovation. The concept of the efficiency of a factor, i.e. its degree of influence, is derived from a mixture of evidence from empirical studies and results of theoretical reasoning. Hypotheses about the efficiency of various factors are presented by Haustein *et al.* (1981).

Looking at the innovation process within the whole social and natural environment, the decision maker must identify socioeconomic opportunities by comparing needs, resources, and the state of the art in all processing systems (Figure 1). We can investigate processing systems using data on, for example, material and energy flows or bottlenecks in the replacement of the labor force with modern technology. We made such an analysis of the innovation cycle in the textile industry of the German Democratic Republic (Haustein 1974). This involved the following steps:

- Draw up a scheme of the technological structure.
- Draw an energy flow diagram.
- Construct a material flow diagram.
- Determine the amount of capital equipment per person or the degree of automation in all elements of the technological structure.
- Determine the range of potential innovations and their ability to overcome loopholes and bottlenecks in the system.
- Evaluate potential innovations.
- Estimate what innovations are lacking.

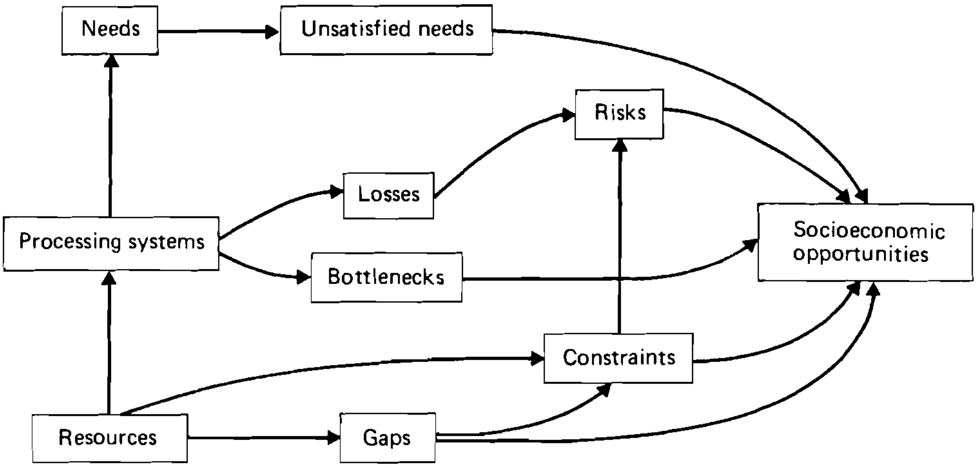

FIGURE 1 Socioeconomic opportunities arising from the relationships between needs, resources, and processing systems.

- Identify innovations of great importance, i.e. that are able to create new imbalances.
- Recommend a technological policy for the whole system.

Table 1 shows a possible scheme for performing such an analysis.

From the standpoint of the organization, the innovation process can be divided into three steps:

1. Establish and develop innovative potential.
2. Realize this potential by initiating and implementing innovations.
3. Ensure that conditions within the organization will allow the new products and processes to have a greater impact on growth and efficiency of the organization.

The potential efficacy of an innovation for a firm can be established only by taking strategic measures, for two reasons: a creative potential cannot be realized by short-term activities; and, in most cases, gaps and bottlenecks in technology transfer cannot be overcome in one year. However, we do not intend to deal here with strategic problems of industrial organizations. Our aim is to analyze the innovation process, which consists of the following steps:

- preparation
- research and development
- investment
- production
- market penetration
- phaseout.

TABLE 1 Scheme for analyzing socioeconomic opportunities according to resource-processing systems.

Main obstacle to efficiency													
Reserve in performance, disclosable by:	New technologies not yet developed												
	New technologies developed but not yet used												
	Increasing performance of auxiliary processes												
	Increasing performance of connected phases and processes												
	Modernization												
Performance (including quality)	Efficiency												
	Limit												
	Actual												
Share of technologies in use (%)													
Technologies in use		A	B	C	D	A	B	C	D	A	B	C	D
Technological level of labor													
Efficiency	Time (%)												
	Energy (%)												
	Material (%)												
Losses	Labor time (man-hours)												
	Energy (Tcal)												
	Weight of material (kt)												
Main processes		A				B				A			
Phase of resource-processing cycle		I								II			

(We can also distinguish three more general stages: invention, technical realization, and commercialization.) The steps are interconnected and often overlap. Only three of them (preparation, production, and phaseout) are inevitable. The time aspect of the innovation process is generally well known, but from the point of view of management it is necessary also to analyze the whole process in terms of the requirements and opportunities for decision making. Therefore, we have combined two dimensions in Table 2: the steps of the innovation process and the stages of the decision process. In this way we can identify where the main delays occur. In the example shown, the whole innovation cycle from event 1a to event 9f lasts more than 19 years. The delay in mass production caused by foreign competitors is relatively high (nine years). The reason for this is the retardation in the first two or three steps of the innovation process and in the preparation of decisions. However, time is only one element of the innovation process.

TABLE 2 Congruence between the innovation and decision processes in the textile industry of the German Democratic Republic.

Innovation process	Decision process						
	a. Appearance of problem	b. First external information	c. Preparation of decisions	d. Decision making	e. Start of implementation	f. End of implementation	Total period (yr)
1. Preparation	1959	1963	1965	1966	1967	1967	8
2. Research	1962	1963	1966	1967	1967	1969	7
3. Development	1963	1963	1968	1969	1969	1972	9
4. Investment preparation	1963	1965	1968	1969	1970	1971	8
5. Investment realization	1964	1966	–	1969	1970	1973	9
6. Start of production	1967	1968	–	1972	1975	1978	11
7. Mass production	1969	1969	–	1974	1975	1978	9
8. Market penetration	1973	1973	–	1974	1974	1978	5
9. Phaseout	–	1980?	–	–	–	1982?	

Theoretically, it is not difficult to include input- and output-related factors such as labor, capital equipment, raw materials, technological risk, unit scale, and funding. Certain relations with the business environment can be modeled fairly accurately, but many other factors have remained outside the project evaluation and selection models reported in the literature, such as interplay of functional rules, characteristics of innovative persons, the economic mechanism, and the management system. We regard such shortcomings to be theoretically rather than practically important: a decision maker in a particular firm is probably not very concerned about most of these factors; in his daily work he concentrates on input- and output-related factors.

Some of the most important relations between the early, predictable characteristics of an innovation project and other variables are presented in Figure 2. Using the model that we have developed, we will look at the early stages of an innovation project, when only rough predictions of the scientific/technological level and range of application of the innovation exist. The scientific/technological level and the range of application determine the next set of variables describing the innovation project:

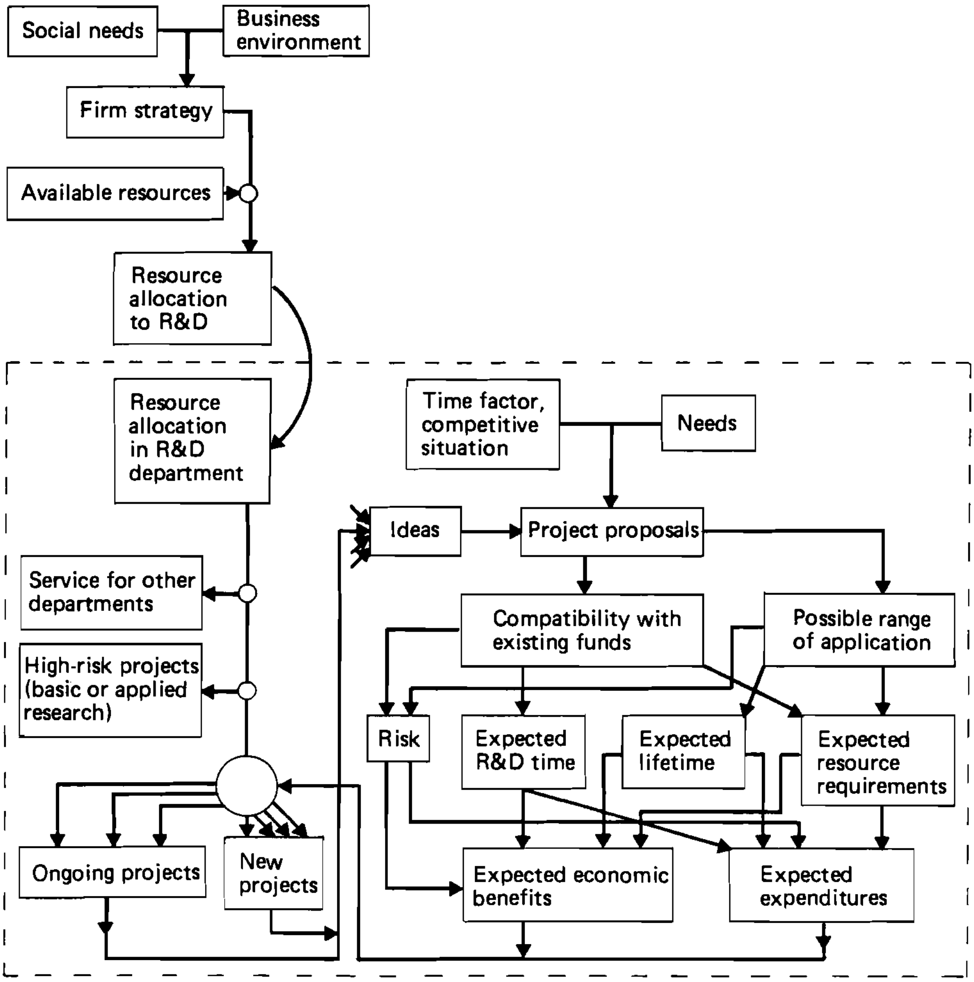

FIGURE 2 The decision-making process for innovation projects. The features and relationships within the broken perimeter are included in the decision support system that has been developed. Open circles indicate decisions.

- complexity
- compatibility with existing equipment
- risk
- expected R&D time
- expected lifetime
- expected resource requirements.

Estimates of these variables, and of expected economic benefits and expenditures, become more and more accurate as the project progresses. One has also to take into account the efficiency of the firm producing the innovation, because the speed with which a new product or process is adopted depends greatly on the benefits to the consumer. This is termed the socioeconomic effectiveness of the innovation.

We shall now summarize the features of innovation decisions that should be taken into account when devising a decision support system for innovation management.

a. Decisions on innovation can only be reversed with considerable losses of efficiency. The further an innovation advances, the more difficult it becomes to reverse the decision to adopt it, because of the manpower involved.
b. Innovation decisions are affected by problems in all economic activities of the firm, e.g. in investment policy, the hiring of manpower, procurement policy, and market strategy (Hennecke 1975).
c. Great uncertainty about further development of adopted projects, future market conditions, etc. complicates decision making. Even in planned economies, resource allocation cannot be predicted exactly.
d. Decision makers have to deal with many conflicting objectives representing both qualitative and quantitative aspects of business. Measurement and comparison of these objectives combine objective and subjective elements. The importance of experience in these matters cannot be overemphasized. The evaluation of alternatives can change rapidly as a result of unforeseen events.
e. Innovations are created not by chemical reactions, but by people (decision makers, research and development specialists, workers), who form groups with often conflicting goals. To be successful, management must create an atmosphere of commitment to the projects eventually selected and weigh the interests of all groups.
f. An innovation project in the lighting industry normally lasts for three to seven years and consists of many steps, although the methodology described in this article does not consider explicitly steps preceding project proposals or following implementation. Hence making decisions on innovation is by nature dynamic and multistage. Every stage has particular problems and sources of uncertainty. Therefore, a lot of partial decisions have to be made in the iterative process of decision making during a project.
g. Decisions have to be made within a certain period, sometimes rather brief. Thus decisions are made sequentially; 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 affect the future of the project (Rapoport 1975).
h. In a planned economy, innovation decisions depend on consultations with higher levels of administration. The more important the innovation, the more time is needed for consultations.

In this study we cannot consider all levels of innovation management (Twiss 1974, ch. 2). There are so many peculiarities among different levels of management that no general recommendations can be given. The higher the level in the management hierarchy, the more complex the decisions become. This is reflected in the number of admissible alternative decisions, the number and quantifiability of the objectives, the complexity of the interdependences among the objectives, and the scope of long-lasting effects (which is difficult to predict). In addition, at higher levels the problems facing management become less structured. This considerably affects the applicability of economic–mathematical methods to the management of innovation projects.

2 A REVIEW OF DECISION SUPPORT MODELS AND THEIR RELEVANCE TO INNOVATION MANAGEMENT

Keen and Morton (1978) define a decision support system (DSS) as computer-based support for management decision makers who are dealing with semistructured problems. The problem of designing an optimal R&D portfolio is often considered unstructured, but this depends in each case on the features of the innovation decisions, which are determined by:

- the complexity of the technical field (number and nature of the relations to other scientific disciplines, technical fields, and industrial branches);
- the age and maturity of the most important product and process innovations, which determine the profile of the technical field under consideration and the dynamics of its development (there is an excellent study by Filippovskii 1978);
- the class of innovations prevailing;
- the position and importance of the technical field (or industrial branch) in the economy as a whole (Haustein and Maier 1980).

Decisions about innovation projects will also display features of uniqueness and/or repetitiveness, with obvious consequences for the degree of support that formal models can give.

Important operations in the decision process are comparing resource requirements and availability and assessing the degree to which new projects can meet the goals of the firm. Thus innovation decisions rely on searches for information on previous experience as well as the application of analytic techniques. Some of the steps in decision processes of this type can be partly delegated to the computer for solution by an interactive mode of operation.

The general approach of DSS starts with the investigation of the key decisions to be made and the determination of which parts of the process are structured and which parts rely on subjective judgment. The decision maker then tries to organize structured subproblems for solution by computerized methods on the basis of appropriate models.

We believe that our approach 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 for further analysis, using other interactive procedures to be discussed later. The first step of the analysis is like the rational framework of decision making; the second step resembles "satisficing" and is closer to real decision making. We do not see DSS as a replacement for widely accepted management tools but as an extension of them.

A DSS based only on an outcome-oriented approach is too limited. Like Zeleny (1976), we define a decision as a dynamic process with feedback loops, search detours, sequential exploration of preferred and feasible sets of alternatives, information gathering, assessment of the structures and goals of the alternatives, and the addition and exclusion of alternatives. Optimization of such a complex system is only possible with a highly simplified model based on many assumptions. Figure 3 presents a simplified version of the process-oriented approach to decision making (details are given by Zeleny 1976).

2.1 Models for Evaluation and Selection of Innovation Projects

A decision support system for innovation management should

- combine outcome-oriented and process-oriented approaches;
- reflect the multistage nature of innovation;
- reflect the uncertainty affecting innovation;
- reflect the mutual dependence between innovation projects;
- take into account the main kinds of resources required in an innovation project;
- be suitable for multiobjective decision making;
- be more or less compatible with existing planning and management systems;
- be suitable for man–machine interaction;
- be based on easily accessible data;
- be based on existing problem-solving techniques that can be easily computerized.

To date no decision support model meeting all these requirements has been constructed.

In practice, the evaluation and selection process consists of at least two steps. The first is a qualitative screening of the proposed innovation projects. Ranking and scoring can help to reject proposals that do not meet certain minimum requirements or that are inferior to other candidates. In this step one can adopt risky basic research or applied research projects with highly uncertain economic parameters. A final decision about whether to continue or reject a proposal is delayed until major uncertainties can be clarified or disappear. In the second step, which is quantitative in nature, the proposed methodology is applied to support the final decision.

Our approach to decision support is based on decision trees. We are convinced that this methodology can be used by the decision maker to coordinate corporate strategy and resource allocation to new and ongoing projects if it is combined with a model for forecasting long-term effects of innovation projects that have been adopted by the firm. The approach is based on certain principles that are common in dynamic and complex situations (e.g.

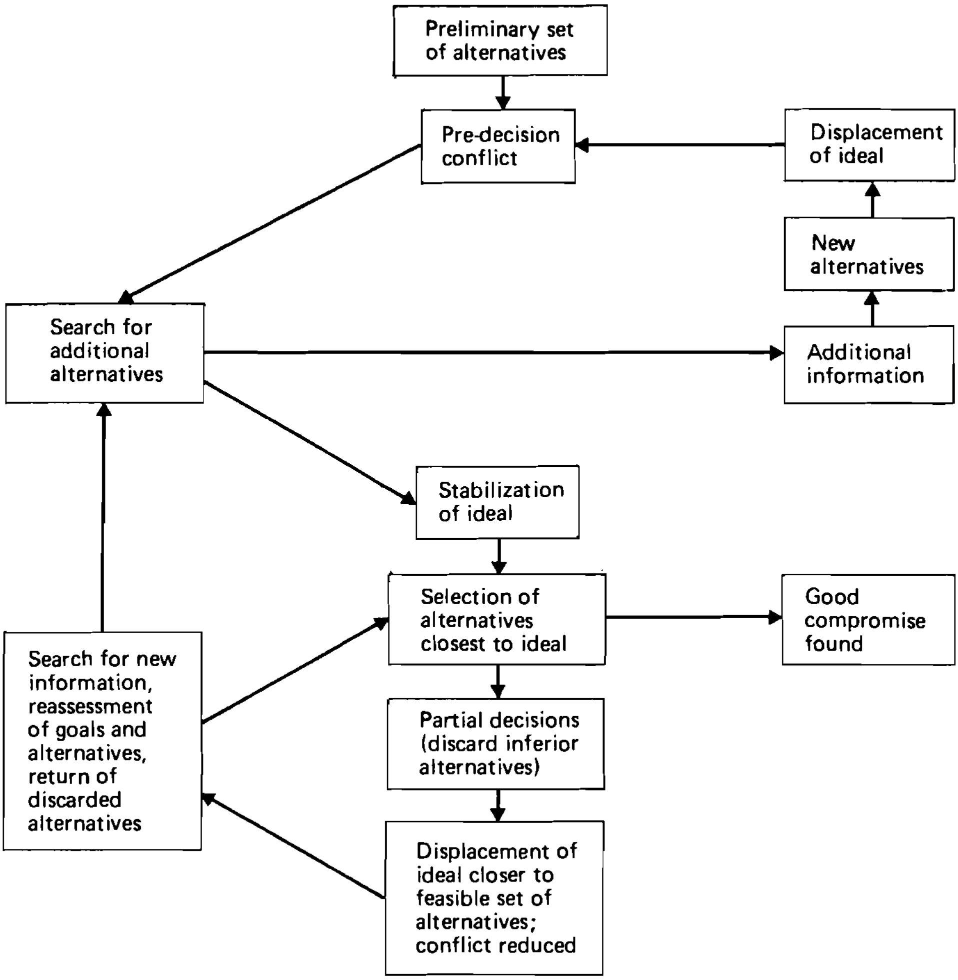

FIGURE 3 Simple process-oriented model of decision making, based on Zeleny's (1976) theory of the displaced ideal. The ideal is defined as the alternative, infeasible in general, that provides the highest score with respect to all individual attributes considered.

Belyaev 1977). Faced with the complexity of the problem, the decision maker and the analyst are forced to simplify reality. The simplifications affect the projects to be considered, the time periods (model horizon and benefit horizon), the number of objectives and their formal representation, the decision maker, and the resources required.

Our model applies only to medium-sized and large projects. A fixed percentage of the budget is spent on all remaining R&D projects and on highly uncertain basic research, which sometimes cannot be related to particular products and processes or has ill defined economic and technical parameters. Research and development management is represented in our model by one decision maker, whose preferences are assumed to be typical of R&D management as a whole. This assumption may be relaxed in the future.

Most of the variables in the proposed model are of a continuous nature. In order to handle the problems, we discretize 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 and extreme values. This simplification greatly eases the task of assessing the probability of future events, because the decision maker is able to perceive significant differences between the options. In discretizing time, we have selected periods of half a year.

In a dynamic environment, where objectives, sets of feasible alternatives, and preferences are constantly changing, optimization of the evaluation and selection process over the whole planning horizon is almost impossible. Under such circumstances, it is necessary to make priority decisions. The optimal solution refers only to the first period. Decisions affecting more distant periods will be reconsidered when the information on them becomes more reliable. The decision process is divided into stages, similarly to the innovation process (Table 2). This is the main idea of the law defining the general structure of the decision-making process for innovation projects in the GDR.

Decisions about innovation projects cannot be made independently, because projects compete for scarce resources, especially for manpower and investments. For this reason, we use a portfolio approach. In order to find an approach appropriate to the problem of decision making in the GDR lighting industry, we shall try to split the problem into classes of decision situation, which will throw light upon possible difficulties in handling it. Danilov-Danilyan (1980) based his classification upon a description of the alternatives (good or bad) and a description of the preferences (good or bad), thereby distinguishing four classes of decision situation. In our case the number of feasible alternatives (project proposals) is known, but a description of them in terms of resource requirements, development time, probabilities of future events, and short- and long-term effects on the firm and on society can only be rather sketchy, at least in the early stages of the innovation process. Obviously, preferences are even less clearly defined. Hence our problem belongs to Danilov-Danilyan's class IV (bad descriptions of both alternatives and preferences), like almost all problems in socioeconomic decision making.

Von Winterfeldt and Fischer (1975) classify decision situations on the basis of three features of the alternatives: the number of attributes, uncertainty, and time (Table 3). An optimal portfolio of innovation projects is characterized by the presence of all three complicating features. The works of Danilov-Danilyan and of von Winterfeldt and Fischer indicate that appropriate models for our case are still lacking at present. The only way to apply formal methods is to neglect one of the features of the preference system, for instance the time variability.

Models for project evaluation and selection have been reviewed elsewhere (Gear *et al.* 1971, Souder 1973a, b, 1978, Clarke 1974, Schwartz 1976) and have been classified by Moore and Baker (1969), Gear *et al.* (1971), Souder (1972), and others. Only very few formal models are in use. Successful implementations of project evaluation models have been reported by Souder

TABLE 3 A classification of choice situations and models (from von Winterfeldt and Fischer 1975).

Case	The choice alternative is:			Model
	Multi-attributed	Uncertain	Time-variable	
1	Yes	No	No	1. Simple-order 2. Riskless trade-off model 3. Additive conjoint measurement
2	Yes	Yes	No	1. Simple expected utility model 2. Riskless decomposition – expected utility model 3. Multiplicative expected utility model 4. Additive expected utility model
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. Expected utility and simple expected utility 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)

(1968), Atkinson and Bobis (1969), Bell and Read (1970), Cochran *et al.* (1971), and Grossman and Gupta (1974). Baker and Pound (1964), Rubenstein (1966), and Ritchie (1970) have cited the following reasons for managers' ignorance of almost all of the models proposed:

- Important aspects of the decision-making process (for instance, uncertainty, the sequential nature of decision making, the interdependence of projects, and multiple criteria) are absent or handled inadequately.
- The models fail to represent the real evaluation and selection process, particularly the roles of experience, intuition, and judgment.
- The necessary input data are lacking.
- There is a lack of mutual understanding between decision makers and analysts.

2.2 The Decision Tree as a Basis for the Proposed Model

Recent developments in modeling the evaluation and selection of R&D portfolios are encouraging (Hespos and Strassman 1965, Gear *et al.* 1970, 1972, Lockett and Freeman 1970, Allen and Johnson 1971, Gillespie and Gear 1972, Lockett and Gear 1972, Gear and Lockett 1973, Gear 1974, Chiu and Gear 1979). Clarke (1974) stated that models involving decision tree analysis have been receiving increasing attention from management scientists. A comprehensive literature survey led us to conclude that for our specific purpose a model using decision trees is most suitable.

A decision tree is a convenient tool for structuring all of a decision maker's ideas about a project. With the help of a decision tree one can represent and analyze a series of partial decisions to be made over time. 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 project has reached a certain degree of maturity and ideas about basic construction, project versions, resource requirements, main sources of uncertainty, development time scale, etc. are relatively well defined. We assume that projects are evaluated and selected over a certain planning horizon, which is divided into periods T. A decision must be made on N projects, each of them with a number of possible paths to completion.

Projects can branch out whenever decision nodes or chance nodes occur. A decision node on the time scale is any point at which the decision maker can influence the progress of the project by making a decision, as a result of which a branch of a given set of possible paths will be selected. Chance nodes are beyond the control of the decision maker and depend on chance events, such as an increase in the price of raw materials or the inability to obtain the necessary machinery within a certain time.

The length of the periods in the model can be chosen so that a decision is made at the beginning of a period. The same assumption can be made about chance events that are supposed to occur before a partial decision is made. The resource requirements are assumed to be known for each time interval and for each version of the project. The number of resource types is specific to each case.

Another model assumption requires that the decision maker be able to assign probabilities to the outcomes of a chance node. This problem will be discussed later (Section 2.3.3.1). All combinations of particular decisions and chance events have some result, which is measured according to scales that correspond to the chosen multiple objectives.

The presentation of innovation projects in the form of decision trees provides the decision maker with several advantages:

- It allows him to see all projects as a whole.
- It allows the representation and adequate handling of interrelated decisions that occur at different times.
- It omits all less important project features.

- It forces the decision maker to use notions, judgments, experience, intuition, and quantitative data for constructing decision trees in an interactive manner.
- It allows early detection of feasible options and bottlenecks.
- It shows the connections between partial decisions and the main sources of uncertainty.
- It combines outcome- and process-oriented approaches to decision making.

Schwartz and Vertinsky (1980) found that the selection of R&D projects is largely dependent on project-specific considerations, such as probability of success (technical and commercial), rate of return, and payback period. Broader 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 strategy." This observation supports our argument for the application of the decision tree to the evaluation and selection of innovation projects, because it provides a better representation of project-specific attributes than of environmental ones.

However, we cannot overlook the several weaknesses and problems inherent in this application of decision trees:

a. Decision trees cannot depict accurately the complexity of factors influencing the real decision-making process. This is true even of quantitative models. Building qualitative factors into the decision tree is not easy and is often a matter of subjective judgment. The problem of whether or not it is possible to apply decision trees to the situation described here is discussed in the literature. Larichev (1979), for instance, questions the value of decision tree analysis for unique decisions. On the other hand, many applications can be cited for problems of this kind (Keeney and Raiffa 1976, Bell *et al.* 1977, Howard 1980).
b. The construction of a decision tree is time-consuming. Often decision makers are unwilling to spend the time necessary to answer analysts' questions about their preference systems, or to provide all of the necessary data at the same time.
c. It is particularly difficult to construct decision trees for the very cases where their application would be most useful: in topics of basic and applied research in their early stages. One must be willing to place a certain degree of confidence in both the objectives and the technical/commercial parameters of the projects.
d. Certain methodological problems have to be solved in a specific way for each case. Among them are inclusion of new project proposals in future periods, the length of the planning horizon (the problem of projects that are not completed within the planned period), the interdependence of projects, transfer of resources, and the degree of detail in the decision tree.

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

f. Decision trees cannot be used to represent the whole lifetime of an innovation. It is impossible to specify the resource requirements more than five to seven years in advance. The kinds of resources required differ considerably from stage to stage. Hence the analyst is forced to aggregate, thereby losing much of the information available. Only very rough figures can be calculated for models based on decision trees. However, this is true of all economic–mathematical models intended for supporting innovation decisions.

g. Sometimes decision trees create the illusion of a freedom of choice, which in reality does not exist because of constraints not formally included in the analysis.

h. The basic model is linear (Section 4).

There are probably other limitations to the approach described in this report, yet, despite its shortcomings, we are convinced that the model can be useful for case studies other than that of the lighting industry, with which our work is concerned.

Not every problem can be solved by applying decision tree methodology alone. For example, Smallwood and Morris (1980) used decision trees only for structuring the decision; they then used underlying and interconnected mathematical models to generate the numbers. First attempts to realize this approach were reported by Gear *et al.* (1970). Other models and techniques, widely accepted in industry, have to be used to provide information:

- models of innovation diffusion (Mansfield *et al.* 1971, Davies 1979);
- models for forecasting manpower requirements;
- models of technological substitution (Linstone and Sahal 1976);
- models for optimal timing of innovations (Barzel 1968, Kamien and Schwartz 1974);
- scenario analysis.

Much research has been carried out on how to facilitate the application of decision trees to innovation management. This work is aimed at

- developing efficient methods for analyzing decision trees (Moskowitz 1971, Marien and Jagetia 1972);
- synthesizing several approaches, including decision trees (Chapman 1979);
- developing new methods for extracting subjective probabilities from the decision maker (Yager 1977);

- lending a foundation to fuzzy decision analysis (Chang and Pavlidis 1977, Watson *et al.* 1979).

On the whole these new efforts mitigate several of the disadvantages of decision trees and make the trees more useful. However, some recently obtained results do not go beyond the stage of theoretical investigations or laboratory tests and are far from being applicable in business (e.g. Watson *et al.* 1979). Finally, these developments rely on equipment that is not yet widely available, even in large firms (e.g. video projectors) (Levin *et al.* 1978).

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 a modular fashion, with diagrams and computations emphasizing communication and robustness rather than precision and generality."

In their combination of fuzzy-sets theory and decision analysis, Watson *et al.* (1979) allow for fuzziness in probabilities and utilities. The authors stress the difference between the imprecision of the input data and the uncertainty of the future state of the world. These qualities are modeled in different ways, using fuzzy-sets theory and probability theory, respectively. Critics attack decision analysis for the imprecision of the data provided by the decision maker ("garbage in – garbage out"). This problem cannot be solved simply with a variable-by-variable sensitivity analysis as it is normally performed, because in reality variables change in combination with one another. Many decision makers are put off by the necessity to provide information in numerical form. Watson *et al.* show that this requirement can be diminished or even replaced. It can be expected that in the future decision makers will provide their assessments of values, utilities, and probabilities in verbal form. The authors point out that they cannot offer an all-purpose tool, but that they can outline the general direction for improving decision analysis.

At Stanford University in California interactive computer graphics are used to compose, decompose, simplify, transform, merge, and regenerate network pictures, including decision trees. The purpose of this system is to accelerate convergence in man–computer experiments, for example by easing the task of drawing decision trees for all projects under consideration. Some of our initial thoughts about the structure of a man–machine system based on decision trees (Section 4) for the selection of innovation projects have been corroborated by the US study. We plan to use some suggestions in the report to improve our system.

Similar efforts were reported by Lewis (1975), Leal and Pearl (1977), and Thompson and Kirschner (1978). Lewis's interactive system for editing tree structures allows insertion, deletion, search, and display of any branch of a given structure. Leal and Pearl described an interactive computer program that was designed and implemented to elicit decision trees from decision makers. This automation of the tedious process of drawing decision trees in a natural-language conversation between decision maker and computer greatly facilitates the distribution of decision analysis techniques.

The technique of Leal and Pearl does not depend on the area of application. All input data provided by the user are mapped into one of the data types (events, actions, likelihoods, relations, etc.). One of the biggest disadvantages of the manual eliciting of decision trees is the danger of spending too much time on details that are irrelevant to the final solution. Leal and Pearl use an efficient tree expansion method that directs effort toward the most critical tip node, defined as the node that is most likely to change the first-step solution currently considered best. The tree expansion method is based on a sensitivity analysis algorithm and on the analogy between decision tree elicitation and heuristic searching on game trees that was first mentioned by Leal and Pearl.

A generalization of these efforts is reported 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.

The systems being developed are becoming increasingly user-friendly and are likely to realize the forecast by Matheson and Howard (1968) that "soon the logical structure of any decision analysis might be assembled from standard components." While we cannot overlook the discrepancy between the inspiring opportunities opened up by researchers and the actual application of those systems in daily decision making, the general direction of computerized decision support systems based on decision analysis seems clear.

2.3 Comparison of Models for Multiobjective Decision Making

Almost all models for innovation project evaluation and selection operate with one objective only. However, discussions with the decision makers in the lighting company used for our case study revealed the necessity to include at least three objective functions, which are not commensurable. We shall discuss later which of the methodologies for multiobjective decision making (MODM) is best suited for the case study. The excellent reviews by MacCrimmon (1973) and Hwang *et al.* (1980) will help to solve our problem of choice because they are based on different classification principles. MacCrimmon stresses the structural differences between the various methods (Table 4); Hwang *et al.* stress the stage at which the information is needed and the type of information (Table 5); and Larichev (1979) concentrates on the type of information provided by the decision maker and its mode of usage (Table 6).

A first glance at the models proposed in the literature indicates that the following classes are worth considering for our case study:

- the method of thresholds of incomparability (Roy and Bertier 1971, Roy 1977, Larichev 1979);
- goal programming (Section 2.3.1);

TABLE 4 Multiobjective/multiattribute decision-making models (MacCrimmon 1973).

A. Weighting methods
    1. Inferred preferences
        a. Linear regression
        b. Analysis of variance
        c. Quasilinear regression
    2. Directly assessed preferences: general aggregation
        a. Trade-offs
        b. Simple additive weighting
        c. Hierarchical additive weighting
        d. Quasiadditive weighting
    3. Directly assessed preferences: specialized aggregation
        a. Maximin
        b. Maximax

B. Sequential elimination methods
    1. Alternative versus standard: comparison of attributes
        a. Disjunctive and conjunctive constraints
    2. Alternative versus alternative: comparison of attributes
        a. Dominance
    3. Alternative versus alternative: comparison of attributes
        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, multicriterion programming

D. Spatial proximity methods
    1. Isopreference graphs
        a. Indifference map
    2. Ideal points
        a. Multidimensional, nonmetric scaling
    3. Graphic preferences
        a. Graphic overlays

- the step method (Section 2.3.2);
- decision analysis (Section 2.3.3);
- the reference point approach (Section 2.3.4).

We shall consider briefly the strengths and weaknesses of four of the classes listed above in order to define options for our case study. We are convinced that not just any model will solve all the problems. For this reason we shall try to implement two or three of them and compare the results obtained (Section 4).

TABLE 5 A taxonomy of methods for multiobjective decision making (from Hwang *et al.* 1980). MOLP, multiobjective goal programming; SEMOPS, sequential multiobjective problem-solving technique; GPSTEM, a combination of goal-programming and STEM methods; SIGMOP, sequential information generator for multiobjective problems.

Stage at which information is needed	Type of information	Major classes of methods
1. No articulation of preference information		1.1.1. Global criterion method
2. *A priori* articulation of preference information	2.1. Cardinal information	2.1.1. Utility function
		2.1.2. Bounded objective method
	2.2. Ordinal and cardinal information	2.2.1. Lexicographic method
		2.2.2. Goal programming
		2.2.3. Goal attainment method
3. Progressive articulation of preference information (interactive methods)	3.1. Explicit trade-off	3.1.1. Method of Geoffrion and interactive goal programming
		3.1.2. Surrogate worth trade-off method
		3.1.3. Method of satisfactory goals
		3.1.4. Method of Zionts–Wallenius
	3.2. Implicit trade-off	3.2.1. STEM and related methods
		3.2.2. SIGMOP method
		3.2.3. Method of displaced ideal
		3.2.4. GPSTEM method
		3.2.5. Method of Steuer (Interactive MOLP method)
4. *A posteriori* articulation of preference information (nondominated solutions generation method)	4.1. Implicit trade-off	4.1.1. Parametric method
		4.1.2. ε-constraint method
		4.1.3. MOLP method
		4.1.4. Adaptive search method

2.3.1 Goal Programming

Goal programming (GP) is frequently proposed to deal with problems with multiple objectives. Surveys of the state of the art have been made by Kornbluth (1973) and Nijkamp and Spronk (1977). The approach has been applied to a large number of practical problems in a wide variety of fields, ranging from manpower planning to environmental protection. Goal programming minimizes a weighted combination of the deviations from a number of goals (target levels, aspiration levels) 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 correlation to recent results of behavioral theory. The following versions have been developed:

- interactive GP (Dyer 1972): according to the classification of Larichev and Polyakov (1980), Dyer's method is pseudostructured and the information required is difficult to obtain (Spronk 1979);

TABLE 6 Larichev's (1979) classification of methods of multiobjective decision making.

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, Keeney and Raiffa 1976, Humphreys 1977).
2.	Direct methods	Decision maker prescribes the form of the aggregation function for the measurement (or assessment) 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) according to the wishes of the decision maker under conditions of unknown probabilities of the states of the world.	
2.3.	Postulation of the aggregation rule; 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 of the alternatives are made in pairs, separately for each criterion. An index is calculated and tested against three thresholds set by the decision maker. The relationship between alternatives is determined as "strongly preferred," "weakly preferred," or "no preference." A ranking is developed from the preference matrix (Roy 1977, Larichev 1979).
5.	Interactive methods	Interactive methods are applied when the model of the choice situation is only partly known. The relations between the criteria are described in an interactive process between decision maker and computer.

- integer multiobjective GP (Lee and Morris 1977, Lee 1978);
- nonlinear GP (Monarchi *et al.* 1976).

Some references provide programs for solving MODM problems using GP. Multiple-goal programming is computationally not very elaborate; many problems can be reduced to linear programming problems, for which standard routines exist. By modifying the basic method, one can deal with a number of specific problems within the framework of GP. For instance, one can weight the deviations and, in this way, show the relative importance of negative or positive deviations.

The drawbacks of GP (large amounts of *a priori* information are required on target levels, weights, etc.) can be avoided by employing interactive approaches.

2.3.2 Step Method

The step method (STEM) is an interactive procedure (with implicit trade-offs between several objectives) for linear programming problems. Thus it can be combined easily with the first formulation of our basic model (Section 4.3). An evaluation by Wallenius (1975) of some interactive procedures indicates that the step method developed by Benayoun *et al.* (1971b) compares favorably with other procedures reported in the literature, most of which are unstructured or pseudostructured.

The step method starts with the construction of a payoff table, which can be done using the computer program designed for our basic model. In this way, the ideal solution is calculated. STEM determines the best compromise in a number of cycles, each consisting of a calculation phase and a decision-making phase. In the calculation phase the feasible solution nearest in a specific sense to the ideal solution is determined. In the decision-making phase the decision maker compares the solution obtained during the last calculation phase with the ideal one and indicates which objectives can be relaxed, and to what extent, in order to improve unsatisfactory objectives. All questions are asked in the specific language of the decision maker, who is asked to think in terms of goal achievement rather than in terms of explicit trade-offs between objectives. The number of cycles is less than the number of objective functions (Benayoun *et al.* 1971a). The authors of STEM suggested versions of their method for three cases:

a. where weights representing the relative importance of the objectives are known;
b. where objectives can be ranked according to their importance to the decision maker;
c. where no information is available about the ranking of the chosen objectives.

Version (b) is applicable to our case study. Modification of the basic STEM algorithm is described in Benayoun *et al.* (1971a).

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

2.3.3 Decision Analysis

The decision analysis group at the Stanford Research Institute in California (Howard and Matheson 1976) characterizes decision analysis as a normative discipline concerned with the practice of rational decision making. What is the basis for the seemingly pretentious assertion by decision analysts that "decision analysis is the most powerful tool yet discovered for ensuring the quality of the decision making process" (Matheson and Howard 1968, Howard and Matheson 1976)?

Decision analysis (DA) was developed especially for complex, uncertain, dynamic situations where decisions have long-term effects. It relies upon Bayesian statistics, subjective assessments of expected utility, multiattribute utility theory, and several methods developed in operations research. The new theory has been applied successfully to a number of practical problems (case studies are described by Howard and Matheson 1976). Advantages of DA include the involvement of the decision maker in the problem-solving process and the consideration of the subjective knowledge, time preference, and attitude to risk of the decision maker.

The early optimism of decision analysts that almost all decision-making problems could be handled by decision analysis has been replaced by more realistic appraisals (e.g. Howard 1980). We see DA as being most useful in economics and less easily applicable to problems with strong social components. Decision analysts admit that some theoretical questions have not yet been solved. Howard and Matheson (1976) have pointed to gaps in the theory, but these "white spots" do not necessarily narrow the range of practical applicability of this new theory.

First tutorials in DA describe it as a normative rather than a descriptive theory. Extensive application work in the last few years has shown that a normative theory must be based on a satisfactory description of the real decision-making process.

Criticism of decision analysis centers on its roots: the assignment of probabilities, the concept of expected utility, and the concept of multiattribute utility.

2.3.3.1 Assignment of Probabilities

The assignment of probabilities to the outcomes of the chance nodes is a part of the concept of expected utility (Section 2.3.3.2). Many theoretical investigations of decision analysis assume that these probabilities are known or are easy to obtain. However, applications of the theory to real decision situations have indicated that this is not true. In the early 1970s psychologists investigated the ability of decision makers to process probabilistic information (Tversky and Kahneman 1975, Kaplan and Schwartz 1975, Slovic *et al.* 1977a, b). The results were disenchanting. Tversky and Kahneman (1975) found that people tend to reduce a complex assessment task to a set of simple tasks using heuristic principles. Under specific circumstances this may lead to questionable decisions resulting from systematic errors in assessment, which in turn are largely the result of certain biases, including the following three types:

a. *Bias due to representation*. Summarizing other studies, Slovic *et al.* (1977a, b) concluded that scientists
    - had unreasonably high expectations about the replicability of results from a single sample;
    - had undue confidence in early results from a few subjects;
    - gambled with research hypotheses based on small samples without realizing the extremely high odds against detecting the effects being studied;
    - rarely attributed unexpected results to sampling variability because they found a causal explanation for every observed effect; and
    - seemed to rely almost exclusively on specific information and neglected prior probabilities.

b. *Bias due to availability*. There is a tendency for people to assess the frequency of a class or the probability of an event by the ease with which instances can be brought to mind (Tversky and Kahneman 1975).

c. *Bias due to anchoring*. In many situations people begin to estimate the probability of an event using a natural starting point (anchor), which is then adjusted. These adjustments are often insufficient.

The question then arises whether these results cast doubt on decision analysis. Although the behavior of people involved in assessment tasks under uncertain conditions was observed to be valid for special laboratory-prepared tests, Slovic *et al.* (1977a, b) 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." Psychologists do not pretend 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 too early to condemn decision analysis. Other considerations support this belief.

The use of probability estimates that are biased to a certain degree will not have catastrophic effects on the results obtained from using the approach proposed in this report. A sensitivity analysis will reveal the importance of a particular estimate for the solution. Several procedures can be applied to calibrate probability assessments (e.g. Spetzler and Stael von Holstein 1972, Lichtenstein *et al.* 1977, Pfohl 1977).

We have to look at the problem of assigning probability to future events in the more general framework of the evaluation process as a whole, including the assignment of values or utilities to certain consequences of our activities. The utility aspect is of the same importance for societal decision making as the probability aspect (Jungermann 1977).

Finally, in tackling problems of high complexity both analyst and decision maker must have the courage to simplify. We cannot renounce probabilities simply because of difficulties in making estimates.

2.3.3.2 Expected Utility Theory

In applying the concept of expected utility, one assumes that decisions are chosen because of their prospects for utility and the probability of the occurrence of certain options. Some decision makers and decision scientists argue, however, that risky decisions are not determined by maximization of expected utility. An alternative theory was suggested by Coombs (1975), but it has not been implemented.

One cannot say definitely whether expected utility is a good or bad basis for making decisions under circumstances of uncertainty. According to Larichev's classification of methods for multiattribute decision making (Table 6), 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 eliminates all problems, but the question is whether or not this postulate is justified.

Kahneman and Tversky reported on an unambiguous violation of the subjectively expected utility theory (Bell *et al.* 1977). They observed that people tend to value consequences that are known with certainty more highly than uncertain consequences. Kahneman and Tversky called this violation the certainty effect.

Another violation of the theory is the reference effect: people seem to evaluate alternatives with reference to a point determined either by expectations about future development or by the status quo. The reference effect is one of the main arguments of the proponents of the reference point approach (Section 2.3.4). The certainty and reference effects must be regarded as serious problems for the normative theory and its application (Slovic *et al.* 1977a, b). Proponents of expected utility could argue that one could elicit the "uncertainty preference" (e.g. risk or time preference) from the decision maker and formally include it in the analysis.

2.3.3.3 Multiattribute Utility Theory

Methods based on multiattribute utility theory (MAUT) are discussed intensively in the scientific literature. Their applicability to real problems has been critically reviewed by Fischer (1972), von Winterfeldt and Fischer (1975), Humphreys (1977), Larichev (1979), and Humphreys and Wisudha (1980). MAUT is a strong and sophisticated mathematical theory (Fishburn 1970) whose main concern is the decomposition of multiattribute utility functions into a set of simple single-attribute utility functions that can actually be assessed. For this purpose a set of axioms has been described (Fishburn and Keeney 1974). However, psychologists have shown that the axioms cannot pretend to be of general applicability (Allais 1953, Slovic and Tversky 1974, von Winterfeldt and Fischer 1975). Disaggregation of the general utility function is often performed regardless of violations of the axioms. Simple additive models are most popular. Several investigations indicate that minor violations had little effect on the quality of the solutions to the problems because of the robustness of the simple additive model (Fischer 1972).

Sometimes the question arises whether it is sensible to spend the considerable effort needed to test the axioms; 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). Recent applications of MAUT placed emphasis not on formal axiomatic considerations but on the specific task environment facing the decision maker. This makes MAUT more attractive for real applications.

Let us summarize the most important drawbacks:

- MAUT assumes that complete and definite information about the preference of the decision maker is available at the beginning of the decision-making process. The opposite seems to be true in most practical situations (Dinkelbach and Isermann 1980, Hwang *et al.* 1980).
- MAUT is based on rather strong assumptions about the rational behavior of economists (Keen and Morton 1978). Investigations by March and Simon (1978) and Wierzbicki (1980) support the hypothesis that everyday decisions are not made by maximizing utility functions but rather by establishing certain reference levels.
- The most important concerns of MAUT are not real decision-making problems but considerations of the form of the disaggregation rule for the overall utility function.
- MAUT is best suited for repetitive choice situations (Wierzbicki 1979a, b, Larichev 1979). (Our problem in the lighting industry is somewhere between the repetitive and unique choice situations.)
- It is extremely difficult to test the axioms.
- MAUT has rarely been applied to risky multiattribute decision making; von Winterfeldt and Fischer (1975) reported only two cases. In most cases additive, riskless, time-invariant models are applied. Hession (1977) discusses risky MAUT procedures, and a case study has been reported by Keefer (1978).
- The procedures for assessing utilities are clumsy, complicated, difficult to understand, and time-consuming; they do not allow for mistakes and they sometimes require answers to somewhat nebulous hypothetical questions (von Winterfeldt 1975).

Bauer and Wegener (1977) ascribe the discrepancy between the sophistication and high development of MAUT and the small number of applications to "limitations concerning the overall complexity that can be processed by it." They state multiattributivity, uncertainty, and time variability to be the main factors determining the complexity of a decision situation and argue that "further decomposition of one of the three dimensions ... has to be paid for with higher aggregation in the other two dimensions, unless progress is made simultaneously on the instrumental side of the modeling techniques, e.g. by introducing choice heuristics or interactive computing assistance."

The weaknesses of MAUT make it difficult to justify its application to our case study. Peschel (1980) points out that despite the great popularity of MAUT in the western scientific literature, the existence of a decision maker's global utility function is sometimes denied. Peschel's reservations are shared by many scientists, especially in countries with planned economies (Golubkov 1977, Belyaev 1977, Danilov-Danilyan 1980).

2.3.4 Reference Point Approach

The following discussion is based on the work of Wierzbicki (1979a, b, 1980), Kallio *et al.* (1980), and Hashimoto (1980). The relatively new reference point approach (RPA) avoids many of the drawbacks of 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 4, where decisions to be made display features of both repetitive and unique decision situations and where the preferences are variable. The problems of an appropriate representation of uncertainty have still to be investigated. Successful implementation of RPA was reported by Hashimoto (1980) and by Kindler *et al.* (1980). A package of programs has been designed for automating RPA, but it is not in general use.

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

A feature of Wierzbicki's approach is that any reference point, attainable or not, can be used. Thus RPA is more general than most of the previous approaches, which used only certain kinds of reference point. Kallio *et al.* (1980) discussed forms of the penalty scalarizing function resulting in linear programming problems. The reference point approach can be combined with our approach as developed in Section 4.

2.4 Risk Evaluation of Portfolios of Innovation Projects

The acceleration of scientific and technological progress amplifies several sources of uncertainty. This greatly complicates decision making on innovation projects and project portfolios. In practice, to ignore risk means to deny the nature of the matter. For this reason, problems of uncertainty and risk are taken up in most publications on decision making. No general recommendations can yet be given on how best to include the prospect of risk in decision making on innovation projects, although there is a need for such a methodology. In this study we can consider only certain theoretical aspects of the problem and possible approaches within the framework of our decision support system for the lighting industry of the German Democratic Republic.

Taking into consideration all complicating aspects (risk, multiple objectives, time variability of the preferences, etc.) independently or sequentially leads to unsatisfactory or, at least, theoretically insufficient results. Models that allow one to handle all these important aspects simultaneously are lacking. New approaches have been developed recently to expand decision making involving multiple objectives to a multicriterion concept of risk (Colson and Zeleny 1980).

Although there are differences between risk and uncertainty, these terms are often seen as identical (Salazar and Sen 1968). In our view, uncertainty denotes ambiguity. We distinguish between uncertainty that can be grasped by probability theory and uncertainty for which probability theory cannot be applied (Fedorenko 1975, p. 376). Furthermore, there is uncertainty resulting from the nature of a process (situation) and uncertainty due to incomplete and/or inaccurate information. In practice these differences become blurred: all types of uncertainty complicate decision making in a like manner.

We have to find the type of uncertainty that best characterizes our problem in order to progress in our investigations. Generally speaking, there are unique choice situations and repetitive choice situations. The decision to adopt or reject an innovation project is either unique or repetitive, depending on the class of innovations prevailing. For example, decisions concerning marginal improvement innovations have many repetitive features, whereas basic innovations are always unique, as are decisions to adopt or reject projects of this type. In our study we deal mainly with average and important improvement innovations (a precise definition of these terms is given by Haustein and Maier 1980). Therefore, an approximate probabilistic treatment of uncertainty seems possible.

The interpretation of uncertainty and risk depends also upon the level of the management hierarchy under consideration. On the level of society as a whole, risk is often associated with uncertain and undesirable consequences of the application of modern technologies (Slovic *et al.* 1977a, b, Paté 1979). Investigations concentrate on psychological questions of perception and societal acceptance of undesirable side effects. While we do not deny the importance of these questions, we stress the influence of uncertain expectations and possible future events on decisions that must be made today concerning innovation projects.

In every business situation, a qualitative risk analysis is absolutely necessary. Quantitative risk analyses are valid only for specific conditions and under certain assumptions and cannot be generalized in most cases. Undoubtedly this fact greatly complicates the integration of risk in the decision-making process within the planned economy. It has not yet been determined whether decision situations can be classified with regard to risk, so that general approaches can be recommended for certain classes.

Let us summarize the most important issues (Bácskai *et al.* 1976, Zellmer 1980). Risk is the possibility that a decision will lead to consequences that differ too much from those expected or planned. This definition relates risk to objectives derived from societal needs. Risk implies interdependence between:

- the objectives of economic development;
- the anticipated objectives and the actual results that can be accepted by society;
- the expected positive consequences;

- the expected negative consequences, should actual results differ too much from those anticipated.

By quantifying these factors in an appropriate manner, we obtain the so-called risk coefficient, as it was introduced by Bácskai *et al.* (1976) and developed further by Zellmer (1980).

A variety of risk factors can lead to a discrepancy between actual and anticipated results. Most of the classifications of these factors reflect peculiarities of a certain field of investigation. For decisions on innovation projects, we see the following factors as most important:

1. The potential areas of application of a particular innovation are only roughly predictable (but accuracy increases with time). This is even more true of the market share of an innovation in a specific application. Difficulties in forecasting the market share are caused, above all, by competing innovations. The market share of a particular innovation is determined by the development of prices (especially the price of energy: Doblin 1982), by existing capacities, by the present economic mechanism and its main directions of development, by the present state of the economy, etc. That is why it is sometimes difficult for innovations to realize the high expectations of top management.
2. To realize its scientific, technological, and economic potential, the innovation process presumes the availability of certain resources, machines, and equipment.
3. Governmental economic measures have a major impact on innovations, especially in countries with centrally planned economies.
4. International development of prices and costs has caused a deeply felt shift in the orientation of the economy as a whole, with profound consequences for all innovation projects under consideration.

All of the factors listed above act together. It is only partly possible to separate them analytically in each application. Other important factors influencing risk are described by Martino (1972), Bácskai *et al.* (1976), and others, who express alternative views on these problems.

Our practical experience with managers and theoretical investigations (Bácskai *et al.* 1976) confirm the view that it is the economic mechanism that has the greatest impact on the formation of risk. The behavior of managers is determined to a high degree by sanctions when risky decisions fail and by financial and other rewards when they succeed. Stimulation has been predominantly negative in nature. This has led most decision makers to shy away from dynamic development with high potential gains for their enterprise and for society as a whole in favor of contemplative, riskless behavior characterized by leisure, stability, and the absence of conflicts. This behavior is also fostered by the fact that risk-prone decision makers lack juridical protection and have insufficient reserve funds. In addition, economic conditions during the 1970s and early 1980s (scarcity of raw materials and energy supplies) have increased restrictions on decision makers' latitude. Governmental agencies are being forced to allocate certain kinds of resources centrally.

Much has been done both in theoretical work and in practice to create an economic mechanism for stimulating decision makers to make decisions involving an admissible degree of risk. We consider risk to be socially admissible if it does not entail possible consequences that could not be accepted by society even when the most important influencing factors are unfavorable. Many of the aids to decision making developed by modern decision theory to quantify risk have been applied successfully to various problems in different branches of industry (e.g. Tsuji 1980 and references cited therein).

We want to warn against uncritical applications of these methods. First of all, the assumptions upon which the methods are based must be examined. All of the methods imply a certain manner or style of viewing a decision problem or place certain aspects of the problem into the center of the analysis (Salazar and Sen 1968, Bácskai *et al.* 1976, Paté 1979, Chapman 1979, Tsuji 1980). In applying methods based on decision theory it is of critical importance to identify all events relevant to a risky decision situation and to determine their interdependence. In order to determine at least the most important of these, the judgment of experts is needed. The quality of the whole analysis depends upon the competence of these experts (Paté 1979).

There are only a few methods that do not employ event probability estimates (behavioral factors producing biases in probability estimates were summarized in Section 2.3.3). Estimates of the probabilities of events provide information that as yet cannot be obtained in other ways.

The application of decision trees is one of the methods suggested by proponents of decision theory for supporting risky decisions. (For details of this and alternative approaches and combinations of methods we refer to the literature, e.g. Belyaev (1977), Keefer (1978), Paté (1979), Chapman (1979), and Tsuji (1980).) A critical assessment of decision trees was made by Larichev (1979). Decision trees are an important element in Cazalet's (1981) integrated system of models. We shall discuss quantitative risk assessment based on decision trees and its integration into our approach after we have introduced the general outline of the decision support system for which we are aiming (Section 4.4).

Having reviewed existing models and concepts for decision support and their relevance to innovation management, we shall now use them for developing a decision support system for the lighting industry. For this purpose we need a clear understanding of the industry and its requirements for development.

3 THE LIGHTING INDUSTRY: A CLASSIC EXAMPLE OF INNOVATION

Energy production and consumption are a major global problem, and society is becoming increasingly aware that economic growth cannot be ensured by the continued ability of energy production to remain ahead of overall production growth. In view of this, many scientific institutions have been making more detailed investigations of a wide spectrum of possible energy-saving measures. Eighty years ago, lighting technology was the biggest consumer of electricity in countries with electric energy systems. The demand for electric lighting and the complex innovation process triggered off by Edison's invention in the late nineteenth century (lighting, energy transmission, energy production) had given rise to the electricity-oriented economy. Throughout the world the amount of electricity consumed for lighting purposes has been increasing for four decades. As an example, Table 7 shows the rise in consumption since 1950 in the German Democratic Republic. There is much interest in the GDR in reducing the consumption of electric energy for lighting by eliminating unnecessary lighting, using light sources more efficiently and effectively, developing new light sources, and making the present sources independent of commercial electricity supplies.

TABLE 7 Development of lighting demand in the German Democratic Republic, 1950–75.

Year	Total electricity consumption (GWh)	Electricity consumption for lighting (GWh)	Average light yield ($\mathrm{lm\ W^{-1}}$)	Light production (Tlmh)
1950	19,466	2,340 (12%)	15	35.2
1955	28,695	3,730 (13%)	20	74.5
1960	40,408	5,250 (13%)	25	131.2
1965	54,101	7,570 (14%)	32	242.0
1970	68,880	10,340 (15%)	36	372.0
1975	85,885	13,800 (17%)	38	524.4

3.1 Developments in Lighting

At present the average efficiency of all existing light sources is only 4–5%. Between 1909 and 1969 the light yield of electric lamps per unit price increased by an average of 6% per year, and the useful life of lamps increased by 3.9%, if we compare the carbon filament lamp and the fluorescent lamp (Willoughby 1969). This corresponds to a rise in light yield per unit cost of 10.1% annually, or a reduction in the price per unit of utilization value by 9.2% annually. This last figure compares favorably with productivity increases in other very dynamic technological sectors.

The potential for light yield is still far from being exhausted. The sodium high-pressure lamp (presently capable of 100–130 lm W^{-1}) and the halogen lamp (presently capable of 30 lm W^{-1}) are examples of innovations that are currently driving the innovation process (Figure 4). None of the known technologies for light generation can guarantee achievement of the long-term goal of producing a light source that is capable of 250 lm W^{-1} and has a useful lifetime of 40,000 h. The useful lifetime of discharge lamps operating by electromagnetic induction instead of electrodes, however,is already estimated to be five to ten years (Carnes 1978).

The light output of the bulb has been increasing since 1880 according to a logistic time function, shown in Figure 4. Starting at about 3 lm W^{-1}, it reached a turning point in 1913 at 8 lm W^{-1} (the highest rate of increase) and did not exceed 12–13 lm W^{-1} in the period 1925–60. All of the partial increases along this logistic curve are to be characterized as evolutionary or partial changes. Most of them are related to the utilization of new and

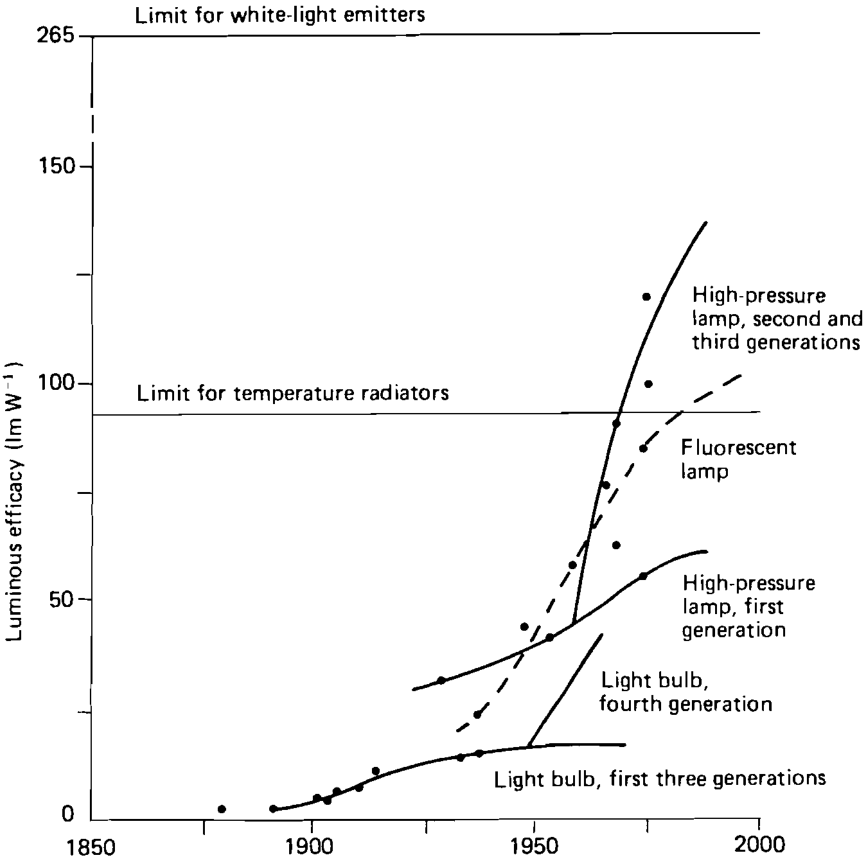

FIGURE 4 Development of the efficacy of light sources.

relatively inexpensive materials, such as krypton (1938).

In 1959, however, a new technological solution was found: the halogen lamp represented a breakthrough to a light output two or three times that of the conventional bulb. It was based on two earlier patents of Scribner (USA, 1882) and van Liempt (Netherlands, 1933). The technological principle applied makes possible a maximum of 58 lm W^{-1}. For light bulbs in general, 95 lm W^{-1} are thought to be feasible (this is the theoretical limit of a Planck radiator at a temperature of 6000 K). The halogen lamp represents a step forward in the development of the light bulb and is a new principle solution of the first order (see Table 9) of the technological principle of resistance heating of a wire, resulting from the application of the action principle of temperature radiation. (This principle solution includes other technological generations, such as the carbon filament lamp, the metallic filament lamp, and the gas-filled, coiled-filament lamp.) Similarly, fluorescent lamps are nothing more than a new technological principle solution in the field of discharge lamps.

Of course, it is possible that new technological principles will be discovered in the field of gas discharge systems. An innovation resulting from such a discovery would have to be classified as a principle solution of the second order. Moreover, only some of the presently known energy transformation processes have been used as commercial light sources. Only three fundamental principles of action have been exploited so far. Plasma physics and the phenomena of tribo-, chemi-, and bioluminescence may find wider application in the future.

3.2 Product and Process Innovations

3.2.1 The Incandescent Lamp

Using the example of the incandescent lamp, we can study the sequence of product innovation and process innovation in the lighting industry (Figure 5). Product innovation began in 1881; until 1891 the technical level of the product, measured in lumen-hours, showed an annual increase. Between 1890 and 1900, during which time gas lighting began to compete with electric lighting, progress was less significant. However, between 1890 and 1915 a series of major improvements (especially ductile tungsten) ensured the success of the new technological principles. At the same time indicators of process innovation behaved differently. Productivity gain was very high when mass production was begun (1882–86); however, it was rather low during the subsequent fifteen years because production was mainly a manual process. Mechanization brought about a greater increase in productivity in the years from 1900 to 1915. As a result of automation the main process innovation came before the Second World War. Product innovation in incandescent lamps declined after 1910–15, but showed a small upswing before the Second World War.

The first halogen lamp was produced in 1960, but it is still not used as a general-purpose lamp. Thus we find that the basic innovation, "incandescent lamp," was realized through three major improvement-related innovations and many minor innovations. The length of the product improvement cycle was about 25–30 years. The increase in technical level of the product reached an absolute maximum in 1910–15, after which there was a decline. Process innovations also went through improvement cycles and became accelerated after the peak in product innovation. After more than forty years of relatively slow product development the bulb production process was revolutionized: only 83 lamps were produced per man-hour in 1939, whereas the corresponding figure for 1969 was 750 (Carnes 1978).

3.2.2 The Discharge Lamp

The innovation process of the discharge lamp began in 1830. The light output was lower than that of the incandescent lamp; however, this should be seen against the higher technological level and greater useful lifetime of the discharge lamp. The production rate increased from 1,000 units per hour in 1954 to more than 3,000 units per hour in 1977. As no new technological principle for light generation has been discovered, it is very difficult today to assess what the time or extent of maximum production of discharge lamps will be.

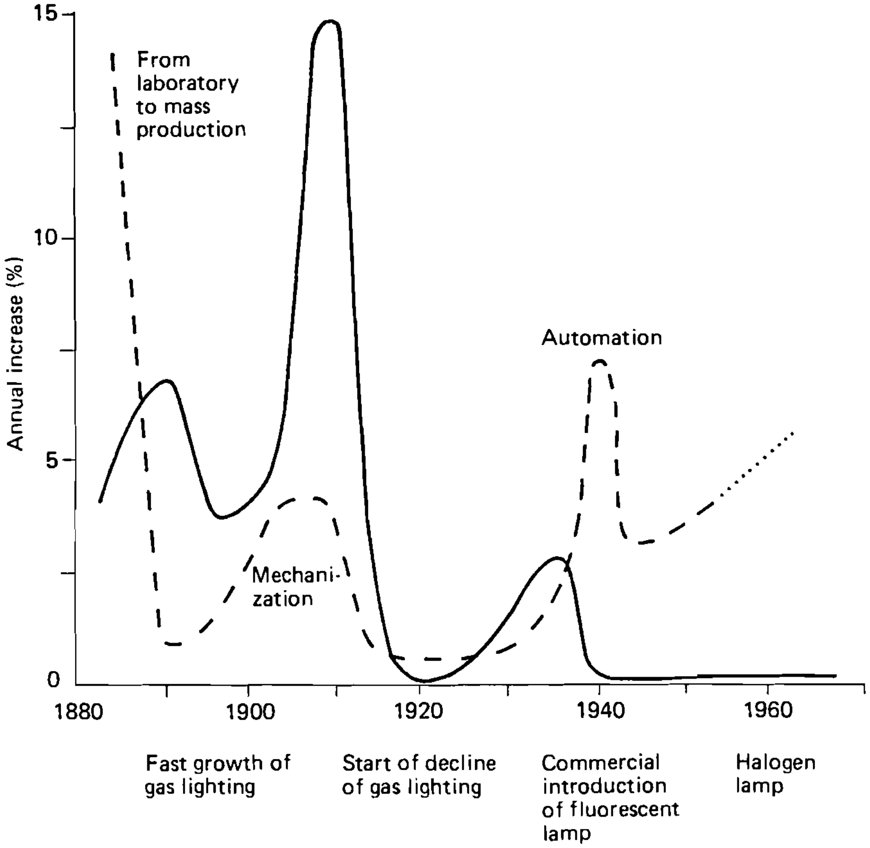

FIGURE 5 The sequence of product and process innovation in the history of the incandescent lamp. Full curve: technical level of the product (lmh); broken curve: productivity (lamps/dollar) (based on data from Bright 1949, Liewald 1977).

The light bulb was the greatest consumer of energy for lighting in the developed countries around 1930. Commercial use of discharge lamps started at about the same time. Discharge lamps are not expected to reach a 95% share in total electric lighting in the developed countries before 1985 (Table 8).

TABLE 8 The production of incandescent lamps and discharge lamps in the German Democratic Republic.

Year	Number of general-purpose lamps produced (millions)	Amount of light produced (Glm)	Number of discharge lamps produced (millions)	Amount of light produced (Glm)	Total amount of light produced (Glm)	Fraction of total produced by discharge lamps (%)
1950	27	18.9	2.6	1.53	20.43	7.5
1951	35	24.5	4.5	2.65	27.15	9.8
1952	44	30.5	3.7	2.18	32.68	6.7
1953	18	12.9	2.8	1.65	14.55	11.3
1954	31	21.7	4.8	2.83	24.53	11.5
1955	44	30.5	7.5	4.41	34.91	12.6
1956	55	38.6	10.5	6.18	44.78	13.8
1957	62	43.3	13.7	8.06	51.36	15.7
1958	65	45.8	17.8	10.48	56.28	18.6
1959	68	47.3	20.4	12.01	59.31	20.2
1960	60	42.0	22.9	13.48	55.48	24.3
1961	58	40.3	23.4	13.77	54.07	25.5
1962	65	45.6	32.3	19.01	64.61	29.4
1963	70	49.1	41.2	24.25	73.35	33.1
1964	75	52.6	44.9	26.43	79.03	33.4
1965	83	58.1	55.0	32.37	90.47	35.8
1966	89	62.3	69.0	40.61	102.91	39.5
1967	92	64.4	74.2	43.68	108.08	40.4
1968	100	70.0	84.9	49.97	119.97	41.7
1969	111	77.7	83.5	49.15	126.85	38.7
1970	111	77.7	114.1	67.16	144.86	46.4
1971	100	77.0	137.7	81.05	158.05	53.7
1972	98	68.6	155.6	91.59	160.19	57.4
1973	93	65.1	158.9	93.53	158.63	59.0
1974	82	57.4	177.1	104.24	161.64	64.5
1975	73	51.1	183.1	107.78	158.88	67.8
1976	76	53.2	189.3	111.42	164.62	67.7

3.2.3 New Light Sources

A recent development is a fluorescent tube that fits into conventional light bulb sockets; this was commercially introduced by Philips in 1979. Another interesting invention that might become an important innovation is the light duct. The Natural Science and Engineering Research Council of Canada recently awarded a $115,000 grant to a team at the University of British Columbia to work on light ducts in collaboration with Vortek Industries Limited. The team will undertake research and development on ducts for carrying large amounts of light from a high-intensity source to a distant location. Light ducts are hollow pipes with specially shaped plastic walls that act as very efficient mirrors, thus allowing the light entering the ducts to be transmitted to the exit with very little loss.

The change in luminous efficacy (expressed in lumens/watt) between 1890 and 1977 can be expressed by

$$y(t) = \frac{265}{1 + \exp\{-[(t - 1977)/22.12]\}}$$

It is thus plausible that by the year $t = 2000$ a light source with an output of 196 lm W^{-1} might be available (Figure 6).

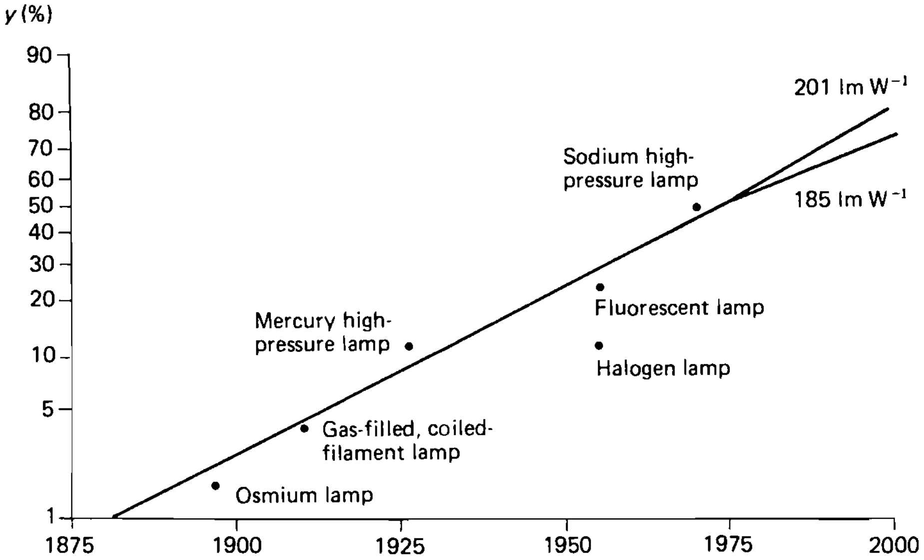

FIGURE 6 Development of efficacy of light sources of the second generation. y = 100% corresponds to 265 lm W^{-1}.

3.3 Classification of Innovations in the Lighting Industry

Table 9 shows a suggested classification of innovations according to the degree of change brought about by a technological principle. A transition to the utilization of another fundamental principle of action rates highest. In this sense the light bulb and the gas discharge lamp are rated as equally important innovations (level 7). However, this is a very general classification; it does not take into account the various degrees of penetration into the laws of nature and into new functional relationships brought about by such innovations. An assessment of future prospects would require a more detailed evaluation.

However, the scientific/technological level represents only one aspect of the innovation process. Its economic counterpart is the extent to which the innovation is actually applied and its efficacy in meeting demand (Table 10). From a historical point of view the light bulb has created a new demand structure and contributed to qualitative changes in national economies (level 6). The discharge lamp, on the other hand, has led to a major modification of the existing demand structure (level 5).

The scientific/technological level i_k and the range of application, or diffusion volume, v_k characterize the valence V of an innovation, where

TABLE 9 Classification of innovations according to scientific/ technological level and material level.

General level	Scientific/technological level	Material level
Partial changes		
1. Quantitative change of the elements of the structure and their proportions.	Quantitative growth of technological base.	Quantitative changes in application of material.
2. Reorganization of the elements of the system's internal structure, supplementation, and adaptation.	Improvement within a known principle solution without major changes.	Further improvement of material properties without major changes.
3. Qualitative changes of individual internal characteristics or functions.	Improvement within a known principle solution, but with major change of one factor (material, technology, function, construction).	Major change in one specific property of material, substitution by other materials.
4. Qualitative change of all internal characteristics, but without change of the basic functional concept.	Improvement within a known principle solution, but with major changes of several factors.	Major changes in several properties of material, new processes for known materials.
Basic changes		
5. Qualitative change with change of basic concept, but without change of the principle behind the concept.	New principle solution of the first order, i.e. within the action principle applied.	Extraction of new materials, discovery and production of new elements and materials.
6. Qualitative change with change of the basic functional principle in the same field of knowledge.	New principle solution of the second order, i.e. replacement of the existing principle by a new one, but within the same change pattern and structural level of matter.	Development of new materials on the basis of molecular processes, major increase of degree of utilization of material.
7. Qualitative changes of the basic functional principle by transition to a new field of knowledge.	New principle solution of the third order, i.e. transition to a different structural level or pattern.	Development of new materials on the basis of elementary processes on the atomic scale. Fundamental increase of degree of utilization of material.

TABLE 10 Classification of innovations according to their range of application in meeting demand.

General level	Range of application
Partial changes	
1. Simple qualitative extension of elements or processes.	Quantitative growth of demand.
2. Quantitative extension of elements or processes.	Modification of existing types of demand (qualitative improvements of existing products).
3. Changed proportions and new properties of elements or processes.	Major modifications of existing types of demand (new properties of known utilization values).
4. Development of new processes and process results in existing economic sectors.	Development of a new type of demand (of a new utilization value) within the existing demand structure.
Basic changes	
5. Qualitative changes of economic sectors (development of new industrial sectors, subsectors).	Major modification of the demand structure by a new utilization value.
6. Qualitative changes of the total economy. Development of new groups of industrial sectors.	Development of a new demand structure. Major change of the proportions of demand.
7. Qualitative changes of the total social and natural environment.	Reorganization of the system.

$V = i_k v_k$ and $k = 0, 1, \ldots, 6$. Forty-nine kinds of innovation are distinguished in Table 11. If we assume that

$$V = e^{ak} e^{bk} = e^{(a+b)k}$$

and assume symmetry of both factors ($a = b$) for the sake of simplicity, then

$$V = e^{2ak}$$

Since $1 \leq V \leq 100$, we find via $100 = e^{12a}$ that $a = 0.38376$. This is the basis for calculating the valence V in Table 11 (also Haustein *et al.* 1981).

Valence is a general historical characteristic but not an operational characteristic. For a comprehensive evaluation of technological principle solutions in the lighting industry the following factors have to be considered (Table 12):

- the age of the solution;
- the average annual increase in the scientific/technological level;
- the average annual decrease in cost per unit of performance;
- the scientific/technological level achieved;

- its actual overall effectiveness; and
- prospects for the technological principle employed.

Table 12 shows that the two new types of high-pressure lamp had reached or exceeded the scientific/technological level and effectiveness of other technological principle solutions within seven to eight years of introduction.

The effectiveness of a technological principle solution in a single field at a certain time is not identical with its historical valence, because the effectiveness is dependent on the following factors:

- the time of introduction;
- original validity;
- the scientific/technological level at the time of introduction and its pattern of development;
- the specific expenditure at the time of introduction and its subsequent decrease;
- the level and development of other, competing principle solutions with respect to technological characteristics and expenditures; and
- the development of economic resources and productivity.

The measurement of effectiveness has become relatively uniform. In a technically simplified way the level of meeting demand could be determined by measuring the amount of illumination, but one must consider more than the quantity of light. The transition toward qualitatively higher demands is caused by people: thus lighting demand has also been determined on the basis of qualitative physiological parameters.

The effort to find suitable measures of the valence or effectiveness of innovations could well be a heuristic stimulus for further development. In this sense the efficacy of a lamp, normally defined as

$$\eta = \frac{\text{useful energy released}}{\text{energy absorbed}}$$

may also be defined in another way:

$$\eta^* = \frac{\text{useful energy released}}{\text{industrially supplied energy + naturally supplied energy}}$$

Accordingly, three variants of light sources are indicated (Haustein 1964):

1. Naturally supplied energy (e.g. environmental heat) is not utilized. This applies to our present light sources.
2. Naturally supplied energy supplements industrially supplied energy, whereby heat is drawn from the environment to produce light. This principle can be utilized by application of the thermoelectric effect to electroluminescence in solid bodies.
3. The logical continuation is that industrially supplied energy is not utilized for lighting, i.e. the light source operates independently of the main supply. A light source that is independent of the main supply and has a nearly unlimited useful lifetime is the ultimate aim of technological development in this field.

TABLE 11 Evaluation of the valences of innovations in the lighting industry.

Scientific and technological level, i_k	Range of application, v_k		
	1. Quantitative growth of demand: $v_1=1.0$	2. Simple modification of existing types of demand (qualitative improvement of products): $v_2=1.5$	3. Major modification of existing types of demand (new properties of known utilization values): $v_3=2.2$
1. Quantitative growth of technological basis: $i_1=1.0$	1.0	1.5	2.2
2. Improvement within a known principle solution without major changes: $i_2=1.5$	1.5	2.3 Improvement of coiled filament lamp, 1950	3.3
3. Improvement within a known principle solution, but with major change of one factor (material, technology, function, construction): $i_3=2.2$	2.2	3.3 Metallic filament lamp, 1905 Coiled filament lamp, 1935 Krypton lamp, 1938	4.8
4. Improvement within a known principle solution, but with major changes of several factors: $i_4=3.2$	3.2	4.8 Gas-filled coiled filament lamp, 1915	7.0
5. New principle solution of the first order, i.e. within the action principle applied: $i_5=4.6$	4.6	6.9	10.1 Halogen lamp, 1959 first applied for floodlights, cars, photography
6. New principle solution of the second order, i.e. replacement of the existing principle by a new one, but within the same pattern and structural level: $i_6=6.8$	6.8	10.2	15.0
7. New principle solution of the third order, i.e. transition to a different structural level of pattern: $i_7=10.0$	10.0	15.0	22.0 Luminous condenser (excitation by electric field), effect discovered in 1921

4. Development of a new type of demand (of a new utilization value) within the existing demand structure: v_4=3.2	5. Major modification of the demand structure by a new utilization value: v_5=4.6	6. Development of a new demand structure. Major change of the proportions of demand: v_6=6.8	7. Reorganization of the system v_7=10.0
3.2	4.6	6.8	10.0
4.8	6.9	10.2	15.0
7.0	10.1	15.0	22.0
10.2	14.7	21.8	32.0
14.7	21.2	31.3	46.0
21.8 Carbon arc lamp, 1877	31.3	46.2	68.0
32.0 Chemiluminescence Bioluminescence	46.0 Discharge lamp, 1930	68.0 Bulb, 1881 (temperature radiation)	100.0

TABLE 12 Evaluation index of technological principle solutions of the lighting industry. The valence of 68 is indexed as 100.

	Valence (Table 11)	Valence standard	First year of production	Annual growth of technological level (%)[a,b]	Annual growth of production per unit of expenditure (%)[a]	Annual growth of effectiveness (%)[a]	Technological level at time of introduction (lmh kW^{-1})[b]	Technological level in 1975 (lmh kW^{-1})[b]	Relative effectiveness in 1975 (%)[c]
1 Bulb	68	100	1881	4.6	2.2	6.9	0.43	32	20
2 Discharge lamp									
2.1 Low-pressure discharge lamp (fluorescent lamp)	46	68	1935	8.9	3.9	13.9	23	638	77
2.2 High-pressure discharge lamp (mercury lamp), excluding 2.2.1 and 2.2.2	46	68	1930	7.2	3.4	12.9	31	660	100
2.2.1 Halide lamp	10	15	1967	22.2	3.7	26.7	140	570	105
2.2.2 Sodium high-pressure lamp	10	15	1968	32.2	2.8	35.9	180	960	125
Total	–	–	–	8.5	2.4	22.2	–	–	–

[a] Annual growth is measured from the first year of production to 1975.

[b] Measured here as the product of lumens and useful lifetime divided by 1 kW (lmh kW^{-1}).

[c] Based on social costs, calculated by Liewald (1977). The calculations include the following quantities: lighting current, useful lifetime, lighting efficiency, lamp costs, installation expenditures, service life, price of light source, annual duration of burning, lamp replacement costs, costs of current, and maintenance costs.

3.4 Lighting Application Systems

In principle, the technological development of specific fields is not unlimited; action principles have physical and technological limits that cannot be exceeded. Sooner or later this leads to a reduction in effectiveness and the transition of a particular innovation process from growth to stagnation or recession. Therefore, we shall now turn away from the limited technological aspects to consider such issues as meeting demands and resource availability. We have the qualitatively and quantitatively growing demand for lighting on one side and the total amount of resources available on the other, with lighting production and application systems (LAS) of various orders in between (Table 13). Lighting technology developed in a complex field encompassing lighting and the production and distribution of electricity. With increasing industrial specialization, lighting technology developed into a relatively narrow field whose main products were lamps (LAS of the first order). Auxiliary devices (connecting devices) and new forms of application were added later (LAS of the second order).

TABLE 13 Components of lighting production and application systems.

Component	First order	Second order	Third order	Fourth order
Source of current				•
Distribution of current				•
Light source	•	•	•	•
Glass or lamp component		•	•	•
Lamp shade			•	•
Auxiliary device		•	•	•
Contracting work for lighting installations			•	•
Application		•	•	•
Lighting project			•	•
Planning and consultancy			•	•

Today development tends toward a higher degree of complexity (LAS of the third order), which, in addition to lamp manufacture, includes planning and application of new utilization systems. Not just lamps but, to a growing extent, whole lighting systems are being produced commercially. In 1978 the lighting technology industry of the German Democratic Republic, which is organized as an LAS of the second order, started to follow up on the development of an LAS of the third order, which is expected to yield much higher effectiveness. The lighting company VEB Narva in Berlin (GDR), which is the firm considered in our case study, is involved today in the production of light sources, lamps, and connecting devices, as well as in other activities.

The effectiveness of an LAS is a complex quantity, and not simply the sum of the effectiveness of the components specified in Table 13. Thus the projection of scientific/technological development should not be confined to individual components; it has to reveal the strategic deficiencies that limit the growth of effectiveness within the overall production and application system. An LAS of the fourth order might be produced in the future, which would return the lighting industry to its starting point, but at a higher scientific/technological level; for example, a lighting system that is independent of the main electricity supply.

A vertical and horizontal combination of production in the production and application systems is the best means of stimulating the dynamic progress of industrial sectors in the interest of the national economy. In this sense the concept of the complex innovation process is clearly defined: it is an innovation process that is not confined to individual components of the production and application process, but that comprises several or all these components.

4 A DECISION SUPPORT SYSTEM FOR THE LIGHTING INDUSTRY

We shall now discuss a decision support system that will help management decide which innovation projects should be adopted and how much to spend on them. The lighting company VEB Narva, which employs 15,000 people, has three objectives for technological progress:

1. Maximization of net production
2. Maximization of exports
3. Maximization of lighting output per unit of energy input.

Clearly, these objectives may conflict with one another to some degree, depending on the level of attainment. This complicates the problem considerably. In designing a decision support system we see no sense in including objectives that are of little importance, because people tend to select alternatives that excel in the more important features (Slovic *et al.* 1977a, b) and because formal complication of the analysis often impairs the decision maker's understanding of the decision situation.

The technological field represented by the lighting company is relatively small and easy to survey. It encompasses about ten basic products stemming from relatively old technological changes. Most of its R&D projects are on improvement-related innovations. The percentage of basic research projects is small enough to be considered negligible. Many of the R&D projects are characterized by relatively well defined technical and commercial parameters.

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

a. Of the set of proposed projects, which should be chosen in order to meet best the goals of the firm and of society as a whole?
b. How many resources should be allocated to which projects? Options include rejection, postponement, termination, or acceleration of ongoing or new projects.

A decision is subject to several constraints. First, the company cannot exceed the amount of resources (including manpower) that it has available or expects to have available. Second, some projects are mandatory and must be adopted although they are not expected to be of economic benefit; for example, they may be necessary for maintaining a market position or for overcoming bottlenecks in the production process. Third, ongoing projects should be coordinated according to the stages of the innovation process so as to avoid excessive demand for certain types of resources at any one time and to maintain continuity in the firm. Fourth, one has to adopt a portfolio of projects that combines innovations that have long-term effects with those that have short-term effects.

In the firm under consideration, corporate strategy is greatly influenced by decisions at the level of the Council of Ministers of the GDR, who determine goals in energy saving. The structure of the decision-making process for innovations is set by law in the GDR. This law defines the main decision points, the documents and expertise required, and the members of the committee of experts who are to make the decision.

4.1 The Basic Approach

It is still too early to speculate about the final form of the decision support system (DSS): this is a long-term goal. In expanding the basic approach, we will rely upon the findings of psychologists, management scientists, and specialists in DSS, and upon experience gained from the implementation of models of R&D project selection. We expect the development of our system to take a few years. Working closely with the decision makers of the firm (who should welcome efforts to make decision making more objective), we will have to decide at each stage whether it is worth while to continue the basic approach. Caution in development is recommended because few successful applications of models of R&D project selection are known, and not many of the recently suggested approaches have been tested in a wide range of practical situations (multiobjective decision making under uncertainty, fuzzy analysis, etc.).

Our procedure was selected because of its flexibility and because of the great number of successful applications to real problems, including the management of R&D, that have been reported. However, further progress in our research will very much depend on the success of our efforts to stimulate support from decision makers and from specialists in a number of disciplines, such as multiobjective decision making, decision analysis, and computer techniques.

A basic principle in the development of a DSS is the modular principle: all of the techniques applied have to be compatible so that the analyst (or decision maker) can combine them at will. This principle guarantees that the model can be adapted to new requirements or to new findings in the rapidly changing field of DSS. We are still searching for the best approach to our problem and this is why we are testing a number of approaches (Section 2.3). In practical applications, hybrid models have often proved successful (Hogarth 1974, Bunn 1978, Chapman 1979).

With our present understanding of the decision situation we think that modules with the following functions are necessary for the decision support system:

1. to process data on innovations that have already been phased out or that have reached an advanced stage;
2. to represent how the manager envisions the development of certain ongoing or new innovations;
3. to forecast important quantities needed for planning innovations (technological and scientific trends, supplies of major resources, development of the firm's capabilities, etc.);
4. to create scenarios;
5. to test long-term effects of strategic decisions on R&D programs (e.g. risk);
6. to process the judgments of experts;
7. to represent the management view of the long-term objectives of the firm; and
8. to secure an efficient man–machine dialogue.

While all of the modules are closely interrelated, they must operate independently so that changes in the organization of the firm will not have catastrophic consequences for the system as a whole.

Our present research is focused mainly on module 2, around which the other modules will be developed step by step. Experience suggests that the process of developing a DSS must be iterative, adaptive, and flexible (Keen 1980). In presenting our first ideas about the DSS, we stimulate the decision maker to specify more precisely his expectations of the support he is to be given.

4.2 Interactive Mode of Operation

Before we discuss the basic model and several versions of it, we must say why an interactive mode of operation is necessary for our case study. When faced with the evaluation and selection of innovation projects under the circumstances of multiple objectives, uncertainty, and the prospect of long-lasting effects on the company as a whole, the decision maker is often unable to articulate his preferences well enough for us to construct a utility function. In most cases, the first presentation of the problem will be very vague and will have to be corrected via feedback loops. This is the main reason for involving the decision maker in the problem formulation and solution and in the evaluation of the results. The decision maker may wish to change some of the data on which the decision tree is based, such as the resource requirements for a certain project path in a particular period, the expected benefits of realizing a particular project, or the probability of certain chance nodes. This might require a reassessment of the impact of the changes on the final outcome. He may even wish to change whole branches of the decision tree.

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 wishes to undertake. Many models for project selection have been rejected because the decision maker felt that his preferences were reflected inadequately. An interactive procedure greatly increases the decision maker's confidence in the method. Zeleny (1980) stated that the "human decision-making paradigm must be amplified rather than ignored, respected rather than degraded." Interactive decision making is the best way to meet this demand.

The main idea behind interactive decision making is jointly to solicit the decision maker's preferences and investigate the feasible alternatives for the eventual determination of an optimal solution. The most important facet of an interactive procedure is the ability of the decision maker to answer the questions asked by the algorithm. One cannot expect him to answer questions that are difficult even with a computer.

Larichev and Polyakov's (1980) classification of interactive procedures is based on the distribution of the work between the decision maker and the machine. They distinguish between unstructured, pseudostructured, and structured procedures, which differ in the degree of involvement of the decision maker in finding a solution. In this report we consider only structured procedures because of their relative simplicity. Structured procedures reflect the results of psychological investigations, that human capabilities for comparing multiattributed alternatives are very limited. Hence interactive procedures should ask simple questions.

4.3 The Basic Model and Different Versions

The basic model can be formulated in several ways, depending on the size of the problem. This is determined by:

- the number of projects under consideration;
- the complexity of the decision trees (numbers of decision and chance nodes and corresponding branches);
- the number of periods;
- the number of types of resources formally included.

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

The decision variable is $x_{ij_t} f_t$, which is the jth path of a project i in period t, and it is assumed that the future state, f, of the world occurs, which is determined by the outcomes of chance nodes up to period t (further details are given by Gear and Lockett 1973). The constraints of this model version ensure that not more than one project path will be selected for each project, that resource availabilities are not exceeded in any of the periods, and that whole paths are either adopted or rejected. Since the values of the end points can be expressed in monetary terms, the objective can be formulated as the maximization of the overall expected sum of the final values of the projects. Similar expressions can be found for the other two objectives mentioned at the beginning of Section 4. Other constraints arising from peculiarities of the firm can be included easily.

The first version of our model takes into account the order in which decisions are due and uncertainties arising in each project over time. Projections of all possible future states of the world are obtained with one computer run. By defining the nodes of the decision tree in an appropriate manner, one can take into account uncertainties about resource requirements, project durations, and project outcomes. The results of the calculations indicate how to allocate the available resources to certain selected projects in period 1 in order to be on the optimum path. If the number of decision variables is large, difficulties may arise in the analysis of the solutions.

From our viewpoint, this first formulation of the problem is well suited for interactive multiobjective decision making and can be combined easily with the step method or the reference point approach (Wierzbicki 1979a, b, 1980, Kallio *et al.* 1980), because all uncertainties involved in the decision trees are represented in the objective function. In solving the problem interactively, the decision maker can manipulate factors 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 solution with the existing standard packages. Moreover, it is possible to reduce the size of a problem that has become too large by reducing the number of chance nodes in the decision trees. The necessary theory for the single-objective case is provided by Lockett *et al.* (1980). Finally, one should be satisfied with a good feasible solution having upper and lower bounds on the expected value of the optimal solution instead of strong optimization, which has no real sense (Lockett *et al.* 1980).

As the size of the linear programming problem increases with the size of the decision tree, it becomes more and more difficult to solve the problem with existing standard solution packages, even when a branch-and-bound method is applied. For this reason, an alternative approach has been developed. It combines linear programming, simulation, and heuristic interpretation of the results. Each path of a given innovation project is represented by one decision variable. The constraints of the model ensure that resource availabilities are not exceeded for any period or for any resource.

In the second problem formulation the chance nodes of the decision trees are sampled repeatedly. In this way the problem is reduced to one of deterministic linear programming. This simulation results in some additional constraints, their number corresponding 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. This approach was first reported by Lockett and Freeman (1970). The application of Monte Carlo techniques has also been proposed by Allen and Johnson (1971). We developed a computer program that generates the corresponding linear programming problem with a fixed matrix of coefficients and a number of right-hand sides for a set of given decision trees. The solutions can be analyzed using statistical means and variances (details are given by, e.g., Lockett and Gear 1973).

This type of presentation of the results of the model runs is very convenient for the decision maker. The proposed method can handle a large number of innovation projects with complicated structures and highly disaggregated resources and periods. A weakness of the method is the problem of final choice. Also, it is not suited for an interactive mode of operation. Nevertheless, it can be used as a convenient starting point for an analysis using the approach discussed above combined with man–machine dialogue. We think that a combination of both approaches is the best way to arrive at the most realistic picture of the whole decision process in innovation projects.

The basic model discussed here is linear. Many detailed studies have indicated that linear models provide good simulations of real R&D situations (Bell and Read 1970, Allen and Johnson 1971), are easy to handle, and are easy for decision makers to understand. They can be easily expanded for multiobjective decision-making problems. (The theory and a number of computer programs for multiobjective linear problems are widely discussed in the literature, e.g. by Evans and Steuer (1973) and Zeleny (1974).) In contrast, nonlinear problem formulations do not add to our understanding of reality and often cannot be solved by standard computerized solution techniques.

4.4 Quantifying Risk and Multiple Objectives

In our approach we use the following notation for quantifying risk:

X	is the set of alternative projects,
x^q	is the portfolio of projects, where $q = 1, 2, 3, \ldots, Q$,
f_k	is the objective function, defined on X, where $k = 1, 2, 3, \ldots, K$,
$f_k(x^q)$	is the benefit with regard to k that is achieved when x^q is realized,
f_k^a	is the aspiration level with regard to the objective function,
r_q	is the risk coefficient when portfolio x^q is realized,
r_{qk}	is the risk coefficient with regard to the objective function when portfolio x^q is realized,
s	is the future state of the world, where $s = 1, 2, 3, \ldots, S$,
p_s	is the probability of the future state s,
$f_k^s(x^q)$	is the benefit with regard to k that is achieved when portfolio x^q is realized, given that state s has occurred.

The risk coefficient r_{qk} is then defined by the following equation (Bácskai *et al.* 1976, Zellmer 1980):

$$r_{qk} = \frac{\displaystyle\sum_{s : f_k^s(x^q) \leq f_k^a} (f_k^a - f_k^s(x^q))p_s}{\displaystyle\sum_{s : f_k^s(x^q) > f_k^a} (f_k^s(x^q) - f_k^a)p_s}$$

In comparing the two versions of the model proposed in Section 4.3, we said that the stochastic programming formulation of the first version is better suited for multiobjective decision making than the combination of linear programming and simulation. This is also true for the quantification of risk using the equation suggested above. Before describing how the first version of the model can be used for evaluating risk in a project portfolio, we shall try to show that in the form introduced the risk coefficient can be used only *a posteriori*, i.e. after we have calculated the optimal solution or several solutions that are considered good enough.

Risk evaluation using decision trees was also suggested by Klausmann (1976), Mäder (1976), and Bácskai *et al.* (1976), but they considered only single projects. By this method risk coefficients can be calculated for all decision alternatives and can be used for decision making (including MODM). However, this approach cannot be applied to our case, where a decision alternative is not identical to a project.

Before calculating risk coefficients we have to determine alternative project portfolios by running the model. In order to use risk coefficients as one of the objectives we would have to follow another approach:

1. Check the admissibility of all possible portfolios.
2. Calculate the risk coefficient for each admissible portfolio.*
3. Select the best portfolio by applying an appropriate decision rule based on the risk coefficients.

Obviously one would have to use an unreasonable amount of computer time for this approach, even if the number of possible portfolios were not very high. The only solution is to calculate the risk coefficients after alternative portfolios have been found. The risk coefficient relates the expected "nonachievement" to the aspiration level and the expected "overachievement." Generally, the lower this coefficient the better the alternative.

Having calculated risk coefficients with regard to K different functions, we have to aggregate them. Zellmer (1980, p. 101) proposed a weighted sum of coefficients for this purpose, using weighting factors that reflect the relative importance of each objective to the decision maker. We hesitate to transfer the aggregation of multiple objectives to the risk coefficients, because the equalization of weighting factors for both the objectives and the risk coefficients has not yet been proven.

An adequate scale is still lacking for the risk coefficients. This problem was recognized by Bácskai *et al.* (1976), who proposed the construction of a risk scale based on an analysis of past experience. Given a risk scale one could define aspiration levels. Other proposals to express risk coefficients in the units of the objectives replace one problem with another (Bácskai *et al.* 1976, pp. 72, 80). For want of anything better, we try to give additional support to the decision maker by calculating the risk coefficients using the equation for the optimal portfolio.

Temporary renunciation of aggregation of the risk coefficients does not rule out future exploitation of the suggestions cited. Obviously risk coefficients cannot be used if the enumeration of all future states of the world is practically impossible. In this case we have to adopt the more traditional approaches for quantifying risk (e.g. Salazar and Sen 1968).

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*To obtain the risk coefficients for nonoptimal admissible portfolios one has to find optimal future decision variables by running the first model version with mandatory projects.

Muhlemann *et al.* (1978) have suggested another approach for incorporating to some degree both multiple objectives and risk into the selection of innovation projects. They formulate the selection problem by stochastic programming to maximize the weighted expected portfolio deviation from a set of goals and show which additional restrictions have to be introduced to realize this special form of goal programming. The decision maker has to define aspiration levels for the set of goals and relative weights per unit of over- or underachievement. The questions of how to define these weights and how to interpret them are discussed by Harrington and Fischer (1980) and Muhlemann and Lockett (1980).

An advantage of this approach is that the relative importance of the objectives is defined on the basis of certain aspiration levels. Moreover, the number of additional constraints is rather low. On the other hand, our notion of risk is better reflected by the risk coefficients.

Muhlemann *et al.* (1978) suggested a number of other approaches for incorporating both risk and multiple objectives, but these add a large number of constraints to the basic formulation (for our purpose quite undesirable) and/or differ too much from our concept of risk. We shall incorporate both risk coefficients and goal programming in order to compare their utility for the decision maker.

Discussions of new approaches in the scientific literature (e.g. fuzzy decision analysis: Freeling 1980) show that their implementation sometimes creates more problems than it solves. In view of this we rely on widely adopted and tested approaches. Useful for almost all approaches (goal programming, step method) is the optimization of the problem separately for each benefit area. The maxima of the different benefits, for instance, can be used in goal programming as the target values, which the decision maker must determine.

The application of the step method (STEM) to our problem seems to be very promising. The first formulation of our problem correlates completely with that considered by Benayoun *et al.* (1971a). The basic STEM is valid when weights of different objectives are known. Our computer programs (Figures 7, 8) can be used to optimize each of the particular objectives mentioned at the beginning of Section 4. Only one step must be added to implement STEM: the optimization of the total objective, which is the weighted sum of the functions of a particular objective. If optimization of the total objective does not provide a satisfactory solution, an additional constraint is introduced that specifies the minimum attainment levels.

4.5 Computer Programs for Two Versions of the Model

In our case study, we programmed both formulations of the problem in the computer language PL1. The programs are being tested on an ES 1020 computer at the University of Economic Sciences in Berlin (GDR). The test versions of the programs operate in batch processing. The algorithms for traversing decision trees are based on a recursive definition of decision trees found in Knuth (1973). Our algorithms are in some respects similar to those reported in the literature (e.g. Bühlmann *et al.* 1975, Mäder 1976, Klausmann

1976, Chung *et al.* 1980). The structures of the computer programs for problem formulations 1 and 2 are shown in Figures 7 and 8, respectively.

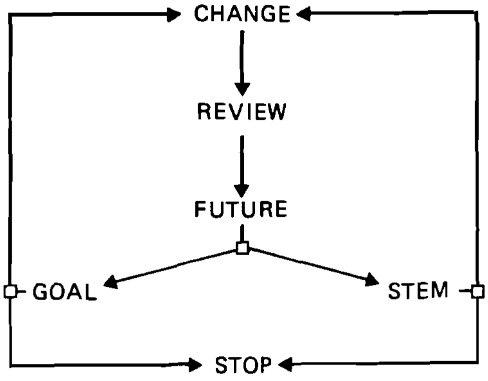

FIGURE 7 Structure of the PL1 program for the first formulation of the problem.

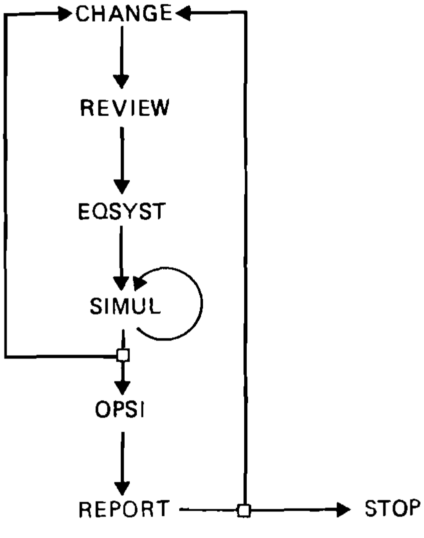

FIGURE 8 Structure of the PL1 program for the second formulation of the problem.

CHANGE is a group of subprograms that stores all input data in the form of lists (Knuth 1973), coordinates man–machine dialogue, and makes changes at the request of the decision maker (e.g. changes in outcomes, resource requirements, resource availability, and probabilities; deletion and insertion of branches; transformation of decision nodes into chance nodes and vice versa; expansion of the model's horizons; changes in time scale; addition of new projects; changes in kinds of resources or benefits). These functions allow high flexibility in the decision trees during implementation of the decision.

CHANGE is applied to both problem formulations, as is the subprogram REVIEW, which allows the decision maker to check the input data and survey the whole portfolio of projects.

FUTURE is a group of subprograms that generates all restrictions for formulation 1. These subprograms are much more complicated than the corresponding subprograms of formulation 2 because we have to generate the restrictions for all possible future states of the world in formulation 1, whereas in formulation 2 this is necessary for only one of them.

EQSYST is a subprogram that generates the matrix of coefficients for the linear programming problem corresponding to the elicited decision tree. For each matrix of coefficients, SIMUL generates a set of right-hand sides of the linear programming problem, which is solved with the standard routine OPSI. What follows is a statistical analysis of the simulation runs using REPORT. Having analyzed the solutions, the decision maker can return to CHANGE and adjust the input data.

In the present program package the decision maker can choose between two methods of MODM: subprogram GOAL adds the necessary constraints for goal programming and the group of subprograms STEM was developed for the step method.

4.6 Results

We shall now demonstrate the operation of the computer programs with a small example of seven project proposals, using five periods, three kinds of resource, and three kinds of benefit (Figure 9 and Table 14). The results of model version 2 show that the following project versions can be excluded from further analysis: P_2V_1, P_3V_1, P_4V_2, P_5V_1, P_7V_1–P_7V_4, P_7V_8, P_7V_{10}, and P_7V_{11}. Project 3 was restructured (aggregation of versions 1 and 2). This simplification reduces the number of possible future states of the world considerably. Model 1 was applied to the simplified portfolio of innovation projects. Results for the three objective functions and their interpretation are given in Tables 15–17.

For objective function 1, there is a high degree of correlation between the results of the two models. Only the fourth project shows differing results. Both models produce the same evaluations of projects 2, 4, 5, and 7 (7: restructure or reject) using objective function 2, but differ for project 3. The results for projects 1 and 6 are complementary. With objective function 3, the models gave the same results for projects 3, 5, and 6, but for the other projects the results must be compared to gain a deeper insight into the choice situation.

From the results in Tables 15–17 we can conclude that:

1. Projects 1 and 2 have been partially selected and should be restructured before a final decision is made on their adoption or rejection.

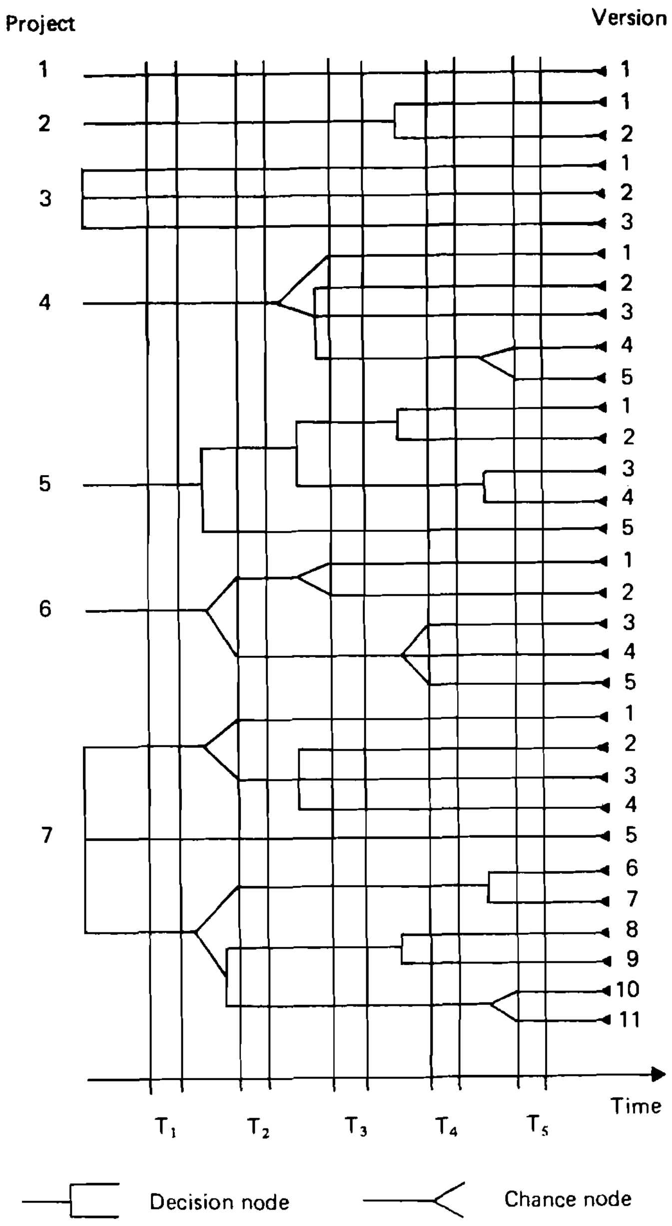

FIGURE 9 Overview of a set of projects.

2. Results for project 3 are contradictory. Project 5 should be adopted (but a decision on how to complete it must be delayed).

TABLE 14 Resource requirements (three types) and benefits (three types) of each project version.

Project version	Resource requirements for each period					Benefits
	T_1	T_2	T_3	T_4	T_5	
P_1V_1	1,1,1	2,1,3	4,2,0	0,2,4	2,2,2	10,12,6
P_2V_1	2,1,2	5,1,0	0,1,4	1,4,3	2,2,1	6,6,7
P_2V_2				0,1,1	2,3,2	13,2,9
P_3V_1	7,2,5	6,4,3	5,0,5	4,0,2	2,1,2	15,3,7
P_3V_2	2,3,3	2,0,0	2,3,2	3,0,0	1,3,3	3,15,7
P_3V_3	1,2,2	2,1,1	3,2,3	3,0,2	5,0,0	7,3,15
P_4V_1	2,0,2	1,3,2	2,2,2	3,0,3	2,0,1	9,9,9
P_4V_2			3,2,2	4,3,2	1,0,2	10,10,10
P_4V_3			2,2,3	0,4,2	0,2,1	15,10,5
P_4V_4			3,2,1	1,2,3	2,3,3	13,12,17
P_4V_5					1,0,4	21,3,16
P_5V_1	0,4,2	2,2,2	1,0,2	2,3,0	2,2,2	6,11,12
P_5V_2				3,0,0	2,2,2	14,2,8
P_5V_3			2,2,0	2,2,4	2,2,2	20,5,10
P_5V_4					2,2,2	5,20,10
P_5V_5		1,1,1	0,0,4	1,1,4	2,2,2	10,5,20
P_6V_1	1,1,1	2,2,2	2,4,3	2,1,4	0,3,3	4,17,6
P_6V_2			1,7,0	4,2,2	3,0,3	13,12,8
P_6V_3		2,2,2	1,4,2	2,2,2	1,7,0	17,15,19
P_6V_4				2,2,2	0,2,2	11,12,8
P_6V_5				2,2,2	0,0,4	25,5,9
P_7V_1	3,3,3	2,2,2	2,2,2	2,2,2	2,2,2	0,25,12
P_7V_2		2,1,1	0,0,4	4,0,0	0,4,0	9,12,15
P_7V_3			2,2,2	1,1,3	1,2,3	10,10,10
P_7V_4			3,2,1	5,0,0	0,4,2	11,17,13
P_7V_5	4,2,1	0,6,2	0,0,6	6,2,0	2,0,2	15,7,12
P_7V_6	1,4,2	2,2,2	3,0,2	0,3,0	4,0,0	20,5,15
P_7V_7					0,0,5	12,20,9
P_7V_8		1,1,1	0,2,2	2,2,1	1,1,1	2,13,13
P_7V_9				4,0,0	0,6,0	15,4,16
P_7V_{10}		0,2,2	1,1,1	1,1,1	0,0,0	9,9,9
P_7V_{11}					0,2,0	13,13,13

3. The adoption of project 4 would be risky, but could contribute high economic benefit to the project portfolio.
4. Project 7 is rejected in most cases.
5. Project 7 must be restructured.

TABLE 15 Results of models 1 and 2 for objective function 1.

Project	Model 1	Model 2
1	0.75 (no unambiguous recommendation)	0.59 (no unambiguous recommendation)
2	0.862 (adoption recommended)	0.61 (no unambiguous recommendation)
3	Rejected	Rejected
4	Adoption recommended (Different recommendations are given about the continuation of project 4 for different future states of the world.)	Rejection recommended
5	Adopted (For all futures P_5V_3 is recommended.)	Adopted (P_5V_3)
6	Rejected	Rejected
7	Adopted (without unambiguous indication of the project version)	Adopted (without unambiguous indication of the project version; restructuring of the project is necessary)

TABLE 16 Results of models 1 and 2 for objective function 2.

Project	Model 1	Model 2
1	0.5 (restructuring of the project might be useful)	Rejected
2	Rejected	Rejected
3	Rejected	0.93 (adoption recommended)
4	Adopted	Mean value of P_4V_3 is 0.81 (adoption recommended)
5	Adopted (P_5V_4)	Adopted (P_5V_4)
6	Adopted	Rejection recommended
7	P_7V_1=0.5	Adopted after restructuring (aggregation)

6. Multiobjective decision-making methods must be applied to give better assistance to the decision maker.

Optimization of the three objective functions yields the following payoff matrix, which can be used as input in the step method for multiobjective decision making:

$$\begin{bmatrix} 67.02 & 41.06 & 51.37 \\ 34.02 & 54.20 & 38.83 \\ 46.67 & 39.73 & 67.60 \end{bmatrix}$$

TABLE 17 Results of models 1 and 2 for objective function 3.

Project	Model 1	Model 2
1	Rejected	Rejected
2	0.58 (no unambiguous recommendation)	0.41 (rejection recommended)
3	Adopted	Adopted
4	Adopted	Adoption possible, but risky
5	Adopted (P_5V_5)	Adopted (P_5V_5)
6	Rejected	Rejected
7	Adopted after restructuring	Adopted after restructuring

TABLE 18 Multiobjective decision making using the step method.

Decision variable	First compromise solution	Second compromise solution (relaxation of objective function 1)	Second compromise solution (relaxation of objective function 2)
$x_{1,1_1}$	0.36091	0.36114	0.59133
$x_{2,1_1}$	0.59563	0.59571	0.74826
$x_{3,1_1}$	0.00	0.00	0.00
$x_{4,1_1}$	1.00	1.00	1.00
$x_{5,1_1}$	1.00	1.00	1.00
$x_{6,1_1}$	0.87738	087710	0.47937
$x_{7,1_1}$	0.22738	0.22751	0.44135
$x_{7,2_1}$	0.77262	0.77249	0.55865
Goal achievement			
Objective function 1	58.90	56.93	59.30
Objective function 2	42.96	44.93	40.25
Objective function 3	61.13	61.65	61.65

TABLE 19 Weights of under- and overachievement used in goal programming.

Overachievement			Underachievement		
Objective function 1	Objective function 2	Objective fuction 3	Objective function 1	Objective function 2	Objective function 3
2.22	1	7.25	1.12	6.75	−0.5

TABLE 20 Results of goal programming.

Decision variable	Solution	Objective function	Value
$x_{1,1_1}$	0.552	1	62.52
$x_{2,1_1}$	0.641	2	42.03
$x_{3,1_1}$	0	3	58.52
$x_{4,1_1}$	1		
$x_{5,1_1}$	1		
$x_{6,1_1}$	0.644		
$x_{7,1_1}$	0.341		
$x_{7,2_1}$	0.659		

The first compromise solution and the following two compromise solutions, calculated after relaxation of the aspiration levels of the first and second objective functions, are listed in Table 18.

Goal programming was used with a system of weights (Table 19) for under- and overachievement. The results are shown in Table 20.

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REFERENCES

Allais, M. (1953) Le comportement de l'homme rationnel devant le risque: Critique des postulats et axiomes de l'école américaine (The behavior of rational man under risk: Critique of the postulates and axioms of the American school). Econometrica 21:503–546.

Allen, D.H., and T.F.N. Johnson (1971) Realism in LP modelling for project selection. R&D Management 1(2):95–99.

Atkinson, A.C., and A.H. Bobis (1969) A mathematical basis for the selection of research projects. IEEE Transactions on Engineering Management EM-16(1):2–8.

Bácskai, T., E. Huszti, D. Keszéna, D. Miko, and J. Szép (1976) A Gazdasagi Kockazat es Meresenek Modszerei (Economic Risk and Methods of its Measurement). Budapest: Kozgazdasagi es Jogi Konyvkiado.

Baker, N.R., and W.H. Pound (1964) R&D project selection: Where we stand. IEEE Transactions on Engineering Management EM-11(4):124–134.

Barzel, Y. (1968) Optimal timing of innovations. Review of Economics and Statistics 50(3):348–355.

Bauer, V., and M. Wegener (1977) Application of multiattribute utility theory: Comments. In: H. Jungermann and G. de Zeeuw (eds.), Decision Making and Change in Human Affairs, pp. 209–214. Dordrecht, Holland and Boston, MA: Reidel.

Bell, D.C., and A.W. Read (1970) The application of a research project selection method. R&D Management 1(1):35.

Bell, D.E., R.L. Keeney, and H. Raiffa (eds.) (1977) Conflicting Objectives in Decisions. International Series on Applied Systems Analysis vol. 1. Chichester, UK: Wiley.

Belyaev, L.S. (1977) A practical approach to choosing alternate solutions to complex optimization problems under uncertainty. Research Memorandum RM-77-7. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Benayoun, R., O.I. Larichev, J. de Montgolfier, and J. Tergny (1971a) Linear programming with multiple objective functions: The method of constraints. Automation and Remote Control, USSR 32(8):1257–1264.

Benayoun, R., J. de Montgolfier, J. Tergny, and O. Larichev (1971b) Linear programming with multiple objective functions: Step method (STEM). Mathematical Programming 1(3):366–375.

Bright, A.J. (1949) The Electric Lamp Industry: Technological Change and Economic Development from 1800 to 1947. New York, NY: Macmillan.

Bühlmann, H., H. Loeffel, and E. Nievergelt (1975) Entscheidungs- und Spieltheorie (Decision and Game Theory). Berlin (West): Springer.

Bunn, D.W. (1978) The Synthesis of Forecasting Models in Decision Analysis. Basle and Stuttgart: Birkhäuser.

Carnes, R.B. (1978) Productivity and technology in the electric lamp industry. Monthly Labor Review 101(8):15.

Cazalet, E.G. (1981) Integrated modeling for analysis of energy policy decisions. Modeling of Large-Scale Energy Systems. IIASA Proceedings Series vol. 12, pp. 109–123. Oxford: Pergamon.

Chang, R.L.P., and T. Pavlidis (1977) Fuzzy decision tree algorithms. IEEE Transactions on Systems Management and Cybernetics SMC-7(1):28–35.

Chapman, C.B. (1979) Large engineering project risk analysis. IEEE Transactions on Engineering Management EM-26(3):78–86.

Chiu, L., and T.E. Gear (1979) An application and case history of a dynamic R&D portfolio selection model. IEEE Transactions on Engineering Management EM-26(1):2–7.

Chung, K.M., F. Luccio, and C.K. Wong (1980) A tree storage scheme for magnetic bubble memories. IEEE Transactions on Computers C-29(10):864–874.

Clarke, T.E. (1974) Decision making in technologically based organizations: A literature survey of present practice. IEEE Transactions on Engineering Management EM-21(2):9–23.

Cochran, M.A., E.B. Pyle III, L.D. Greene, H.A. Clymer, and A.D. Bender (1971) Investment model for R&D project evaluation and selection. IEEE Transactions on Engineering Management EM-18(3):89–100.

Colson, G., and M. Zeleny (1980) A multicriterion concept of risk under incomplete information. Computers and Operations Research 7:125–143.

Coombs, C.H. (1975) Portfolio theory and the measurement of risk. In: M.F. Kaplan and S. Schwartz (eds.), Human Judgment and Decision, pp. 63–85. New York, NY: Academic Press.

Danilov-Danilyan, V.I. (1980) Metodologicheskie aspekty i teoriya sotsialno-ekonomicheskogo optimuma (Methodological aspects and theory of socioeconomic optima). Ekonomika i Matematicheskie Metody 16(1):146–164.

Davies, S. (1979) The Diffusion of Process Innovations. Cambridge: Cambridge University Press.

Dinkelbach, W., and H. Isermann (1980) Resource allocation of an academic department in the presence of multiple criteria – Some experiments with a modified STEM network. Computers and Operations Research 7(1):99–106.

Doblin, C.P. (1982) The growth of energy consumption and prices in the USA, FRG, France, and the UK, 1950–1980. Research Report RR-82-18. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Dyer, J.S. (1972) Interactive goal programming. Management Science 19(1):62–70.

Evans, J.P., and R.E. Steuer (1973) A revised simplex method for linear multiple objective programs. Mathematical Programming 5:54–72.

Fedorenko, N.P. (ed.) (1975) Matematika i Kibernetika v Ekonomike (Mathematics and Cybernetics in Economics). Moscow: Ekonomika.

Filippovskii, E.E. (1978) Obnovlenie Promyshlennoi Produktsii v Kapitalisticheskich Stranakh (Innovation in Capitalist Countries). Moscow: Nauka.

Fischer, G.W. (1972) Four methods for assessing multiattribute utilities: An experimental validation. Technical Report 037230-6-T. Ann Arbor, MI: Engineering Psychology Laboratory, University of Michigan.

Fishburn, P.C. (1970) Utility Theory for Decision Making. New York, NY: Wiley.

Fishburn, P.C., and R.L. Keeney (1974) Seven independence concepts and continuous multiattribute utility functions. Journal of Mathematical Psychology 1:294–327.

Freeling, A.N.S. (1980) Fuzzy sets and decision analysis. IEEE Transactions on Systems, Man, and Cybernetics SMC-10(7):341–354.

Gear, A.E. (1974) A review of some recent developments in portfolio modeling in applied R&D. IEEE Transactions on Engineering Management EM-21(4):119–125.

Gear, A.E., J.S. Gillespie, and J.M. Allen (1972) Applications of decision trees to the evaluation of applied research projects. Journal of Management Studies, May, pp. 172–181.

Gear, A.E., J.S. Gillespie, A.G. Lockett, and A.W. Pearson (1970) Manpower modeling: A study in research and development. Paper presented at Conference of Institute of Management Science, London, July.

Gear, A.E., and A.G. Lockett (1973) A dynamic model of some multistage aspects of research and development portfolios. IEEE Transactions on Engineering Management EM-20(1):22–29.

Gear, A.E., A.G. Lockett, and A.W. Pearson (1971) Analysis of some portfolio selection models for R&D. IEEE Transactions on Engineering Management EM-18(2):66–76.

Gillespie, J.S., and A. E. Gear (1972) Decision network in applied research and development. Proceedings of INTERNET Conference, Stockholm, May, pp. 128–147.

Golubkov, E.P. (1977) Sistemnyi Analiz v Otraslevom Planirovanii (Systems Analysis in the Planning of Industrial Branches). Moscow: Ekonomika.

Grossman, D., and S.N. Gupta (1974) Dynamic time-staged model for R&D portfolio planning: A real world case. IEEE Transactions on Engineering Management EM-24(4):141–147.

Harrington, T.C., and W.A. Fischer (1980) Portfolio modeling in multiple-criteria situations under uncertainty: Comment. Decision Sciences 11(1):171–177.

Hashimoto, T. (1980) A multiobjective approach to allocating water resources for municipal, agricultural, and recreational uses. Working Paper WP-80-107. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Haustein, H.-D. (1974) Die Proportionalität der Technischen Basis im Sozialismus. Berlin (GDR): Akademie-Verlag.

Haustein, H.-D. (1964) Die Messung und ökonomische Analyse des technischen Niveaus unter besonderer Berücksichtigung der Anforderungen der Perspektivplanung (Measurement and economic analysis of technical levels with particular consideration for future planning requirements). Habilitation Thesis, University of Economics, Berlin (GDR).

Haustein, H.-D., and H. Maier (1980) Basic, improvement, and pseudo-innovations and their impact on efficiency. Technological Forecasting and Social Change 16:243–265.

Haustein, H.-D., H. Maier, and L. Uhlmann (1981) Innovation and efficiency. Research Report RR-81-7. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Hennecke, H.-U. (1975) Verfahren zur Bewertung von Vorschlägen für industrielle Forschungs- und Entwicklungsprojekte (Method for assessing proposals for industrial research and development projects). Dissertation, University of Saarland, FRG.

Hespos, R.F., and P.A. Strassman (1965) Stochastic decision trees for the analysis of investment decisions. Management Science 11(10):244–259.

Hession, E. (1977) The application of multiattribute utility models to some uncertain decision situations in areas of business and public policy. In: H. Jungermann and G. de Zeeuw (eds.), Decision Making and Change in Human Affairs, pp. 67–80. Dordrecht, Holland and Boston, MA: Reidel.

Hogarth, R.M. (1974) Process tracing in clinical judgment. Behavioral Science 19:298–313.

Howard, R.A. (1980) An assessment of decision analysis. Operations Research 28(1):4–27.

Howard, R.A., and J.E. Matheson (eds.) (1976) Readings in Decision Analysis. Menlo Park, CA: Stanford Research Institute.

Humphreys, P. (1977) Application of multiattribute utility theory. In: H. Jungermann and G. de Zeeuw (eds.), Decision Making and Change in Human Affairs, pp. 165–208. Dordrecht, Holland and Boston, MA: Reidel.

Humphreys, P., and A. Wisudha (1980) MAUT – An interactive computer program for the structuring, decomposition, and recomposition of preferences between multiattributed alternatives. Technical Report 79-2/2. Uxbridge, UK: Brunel Institute of Organization and Social Studies, Decision Analysis Unit.

Hwang, C.L., S.R. Paidy, K.Yoon, and A.S.M. Masud (1980) Mathematical programming with multiple objectives: A tutorial. Computer and Operations Research 7(1–2):5–31.

Jungermann, H. (1977) Cognitive processes and societal risk taking: Comments. In: H. Jungermann and G. de Zeeuw (eds.), Decision Making and Change in Human Affairs, pp. 37–44. Dordrecht, Holland and Boston, MA: Reidel.

Kallio, M., A. Lewandowski, and W. Orchard-Hays (1980) An implementation of the reference point approach for multiobjective optimization. Working Paper WP-80-35. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Kamien, M.I., and N.L. Schwartz (1974) Patent life and rivalry. American Economic Review 64(1):183–187.

Kaplan, M.F., and S. Schwartz (eds.) (1975) Human Judgment and Decision Processes. New York, NY: Academic Press.

Keefer, D.L. (1978) Allocation planning for R&D with uncertainty and multiple objectives. IEEE Transactions on Engineering Management EM-25(1):8–14.

Keen, P.G.W. (1980) Decision support systems: A research perspective. Sloan Working Paper 1117-80. Cambridge, MA: Center for Information Systems, MIT.

Keen, P.G.W., and M.S.S. Morton (1978) Decision Support Systems: An Organizational Perspective. Reading, MA: Addison–Wesley.

Keeney, R.L., and H. Raiffa (1976) Decisions with Multiple Objectives. New York, NY: Wiley.

Kindler, J., P. Zielinski, and L. de Mare (1980) An interactive procedure for multiobjective analysis of water resources allocation. Working Paper WP-80-85. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Klausmann, H.-S. (1976) Stochastische Entscheidungsbäume: Ein Beitrag zur Lösung von sequentiellen Entscheidungsproblemen bei Risiko (Stochastic Decision Trees: A Contribution to Solution of Decision Problems with Risk). Meisenheim am Glan, FRG: Verlag Glan.

Knuth, D.E. (1973) The Art of Computer Programming vol. 1. New York, NY: Addison–Wesley.

Kornbluth, J. (1973) A survey of goal programming. OMEGA 1:193–205.

Larichev, O.I. (1979) Nauka i Iskusstvo: Prinyatiya i Reshenii (Science and Art of Decision Making). Moscow: Nauka.

Larichev, O.I., and O.A. Polyakov (1980) Cheloveko–mashinnye protsedury resheniya mnogokriterialnykh zadach matematicheskogo programmirovaniya (Man–machine procedures for solving mathematical programming problems with multiple objectives). Ekonomika i matematicheskie metody 16(1):129–145.

Leal, A., and J. Pearl (1977) An interactive program for conversational elicitation of decision structures. IEEE Transactions on Systems, Man, and Cybernetics SMC-7(5):368–376.

Lee, S.M. (1978) Interactive integer goal programming: Methods and applications. In: S. Zionts (ed.), Multiple Criteria Problem Solving, pp. 362–383. Berlin (West): Springer.

Lee, S.M., and R.L. Morris (1977) Integer goal programming methods. TIMS Studies in the Management Sciences 6:273–289.

Levin, S., S. Johnston, A. Leal, and G. Weltman (1978) Computer-based group decision aiding. Proceedings of the IEEE International Conference on Cybernetics and Society, 3–8 November, Tokyo–Kyoto, Part II:707, pp. 1396–1401.

Lewis, J.W. (1975) Tree: An interactive system for editing tree structures. Computing and Graphics 1(1):65–68.

Lichtenstein, S., B. Fischhoff, and L.D. Phillips (1977) Calibration of probabilities: The state of the art. In: H. Jungermann and G. de Zeeuw (eds.), Decision Making and Change in Human Affairs, pp. 275–324. Dordrecht, Holland and Boston, MA: Reidel.

Liewald, H. (1977) Die analytisch–prognostische und langfristig–konzeptionelle Arbeit für Forschung und Entwicklung als Bedingung für die planmässige Erhöhung des wissenschaftlich–technischen Niveaus der Produktion – Dargestellt am Beispiel der Lichtquellen-Industrie der DDR (Analytic–predictive and long-term planning of research and development work as a condition for the systematic increase of the scientific–technical level of production – The example of the lighting industry of the GDR). Dissertation, Humboldt University, Berlin (GDR).

Linstone, H.A., and D. Sahal (eds.) (1976) Technological Substitution, Forecasting, Technique, and Applications. Portland, OR: Portland State University.

Lockett, A.G., and P. Freeman (1970) Probabilistic networks and R&D portfolio selection. Operational Research Quarterly 21(3):353–359.

Lockett, A.G., and A.E. Gear (1972) Program selection in research and development. Management Science 18(10):575–590.

Lockett, A.G., and A.E. Gear (1973) Representation and analysis of multistage problems in R&D. Management Science 19(8):947–960.

Lockett, A.G., A.P. Muhlemann, and L.A. Wolsey (1980) A stochastic programming model for project selection. In: M.A.H. Dempster (ed.), Stochastic Programming, pp. 427–448. New York, NY: Academic Press.

MacCrimmon, K.R. (1973) An overview of multiple objective decision making. In: J. Cochrane and M. Zeleny (eds.), Multiple Criteria Decision Making, pp. 18–44. Columbia, SC: University of South Carolina Press.

Mäder, M. (1976) Aufbau und Analyse von Entscheidungsbäumen: Grundlage für die Entwicklung eines computergestützten Analyseverfahrens für Risikoentscheidungsprobleme (Construction and analysis of decision trees: Basis for the development of a computer-assisted analytical technique for risk decision problems). Dissertation, University of St. Gallen, Switzerland.

Mansfield, E., J. Rapoport, J. Schnee, S. Wagner, and M. Hamburger (1971) Research and Innovation in the Modern Corporation. New York, NY: Macmillan.

March, J.G., and H.A. Simon (1978) Organizations. New York, NY: Wiley.

Marien, E.., and L.C. Jagetia (1972) A solution approach to the calculation of expected, discounted decision values for new-product sequential-decision processes. Bulletin of the Institute of Management Science, March, p. 121.

Martino, J.P. (1972) Technological Forecasting for Decisionmaking. New York, NY: American Elsevier.

Matheson, J.E., and R.A. Howard (1968) An Introduction to Decision Analysis. Palo Alto, CA: Stanford Research Institute.

Monarchi, E.D., J.E. Weber, and L. Duckstein (1976) An interactive multiple objective decision making aid using nonlinear goal programming. In: M. Zeleny (ed.), Multiple Criteria Decision Making, pp. 235–253. Berlin (West): Springer.

Moore, J.R., Jr., and N.R. Baker (1969) Computational analysis of scoring models for R and D project selection. Management Science 16(4):B212–232.

Moskowitz, H. (1971) Dynamic programming and branch and bound approaches for analyzing decision trees in normal form. Paper presented at 39th National Meeting of Operations Research Society of America, Dallas, TX, 5–7 May.

Muhlemann, A.P., and A.G. Lockett (1980) Portfolio modeling in multiple-criteria situations under uncertainty: Rejoinder. Decision Sciences 11(1):178–180.

Muhlemann A.P., A.G. Lockett, and A.E. Gear (1978) Portfolio modeling in multiple-criteria situations under uncertainty. Decision Sciences 9(4):612–626.

Nijkamp, P., and J. Spronk (1977) Goal programming for decision making. Report 7709/A. Rotterdam: Erasmus University, Centre for Research in Business Economics.

Paté, M.-E. (1979) Values and risks – A research proposal for IIASA. Working Paper WP-79-94. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Peschel, M. (1980) Ingenieurtechnische Entscheidungen: Modellbildung und Steuerung mit Hilfe der Polyoptimierung (Technical Engineering Decisions: Model Construction and Control with the Aid of Multicriteria Optimization). Berlin (GDR): Verlag Technik.

Pfohl, H.-C. (1977) Messung subjektiver Wahrscheinlichkeiten (Measurement of subjective probabilities). In: H.-C. Pfohl and B. Ruerup (eds.), Wirtschaftliche Messprobleme (Economic Measurement Problems), pp. 23–36. Cologne: Hanstein Verlag.

Rapoport, A. (1975) Research paradigms for studying dynamic decision behavior. In: D. Wendt and C. Vlek (eds.), Utility, Probability, and Human Decision Making, pp. 349–369. Dordrecht, Holland and Boston, MA: Reidel.

Ritchie, E. (1970) Research on research: Where do we stand? R&D Management 1(1):3–9.

Roman, D. (1980) Science, Technology, and Innovation: A Systems Approach. Columbus, OH: Grid.

Roy, B. (1977) ELECTRE III. Sema, Research Report 81.

Roy, B., and P. Bertier (1971) La Méthode ELECTRE II. Sema, Note de Travail 124.

Rubenstein, A.H. (1966) A real firm study of information requirements for project selection in research and development. Paper presented at International Federation of Operations Research Societies, Boston, MA, August.

Salazar, R.C., and S.K. Sen (1968) A simulation model of capital budgeting under uncertainty. Management Science 15(4):161–179.

Schwartz, S.L (1976) R&D project evaluation: From firm behavior to normative models to implementations. Report IV/76-2. International Institute of Management, Berlin (GDR).

Schwartz, S.L., and I. Vertinsky (1980) Information preferences and attention patterns of R&D investment decision. In: D. Sahal (ed.), Research, Development, and Technological Innovation. Lexington, MA: Heath.

Slovic, P., B. Fischhoff, and S. Lichtenstein (1977a) Behavioral Decision Theory. Annual Review of Psychology 28:1–39.

Slovic, P., B. Fischhoff, and S. Lichtenstein (1977b) Cognitive processes and societal risk taking. In: H. Jungermann and G. de Zeeuw (eds.), Decision Making and Change in Human Affairs, pp. 7–36. Dordrecht, Holland and Boston, MA: Reidel.

Slovic, P., and A. Tversky (1974) Who accepts Savage's Axiom? Behavioral Science 19:368–373.

Smallwood, R.D., and P.A. Morris (1980) A task force decision analysis. Operations Research 28(1):60–80.

Souder, W.E. (1968) Experiences with an R&D project control model. IEEE Transactions on Engineering Management EM-15(1):39–49.

Souder, W.E. (1972) Comparative analysis of R&D investment models. AIIE Transactions 4(1):57–64.

Souder, W.E. (1973a) Analytical effectiveness of mathematical networks for R&D project selection. Management Science 19(8):907–923.

Souder, W.E. (1973b) Utility and perceived acceptability of R&D project selection models. Management Science 19(12):1384–1394.

Souder, W.E. (1978) A System for using R&D project evaluation methods. Research Management 21(5):29–37.

Spetzler, C.S., and C.A.S. Stael von Holstein (1972) Probability encoding in decision analysis. In: R.A. Howard and J.E. Matheson (eds.), Readings in Decision Analysis, pp. 405–427. Menlo Park, CA: Stanford Research Institute.

Spronk, J. (1979) Interactive multiple-goal programming as an aid for capital budgeting and financial planning with multiple goals. Report 7914/F. Rotterdam: Erasmus University, Centre for Research in Business Economics.

Thompson, D.A., and P. Kirschner (1978) Decision trees display parameters for interactive graphics computers. Proceedings of International Conference on Interactive Techniques in Computer-Aided Design, pp.363–366. New York: IEEE.

Tsuji, K. (1980) The effects of uncertainty in generation expansion planning: A review of methods and experiences. Working Paper WP-80-116. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Tversky, A., and D. Kahneman (1975) Judgment under uncertainty: Heuristics and biases. In: D. Wendt and C. Vlek (eds.), Utility, Probability and Human Decision Making, pp. 141–163. Dordrecht, Holland and Boston, MA: Reidel.

Twiss, D.C. (1974) Managing Technological Innovation. London: Longman.

Wallenius, J. (1975) Comparative evaluation of some interactive appoaches to multicriterion optimization. Management Sciences 21(12):1387–1396.

Watson, S.R., J.J. Weiss, and M.L. Donnell (1979) Fuzzy decision analysis. IEEE Transactions on Systems, Man, and Cybernetics SMC-9(1):1–9.

Wierzbicki, A.P. (1979a) The use of reference objectives in multiobjective optimization – Theoretical implications and practical experience. Working Paper WP-79-66. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Wierzbicki, A.P. (1979b) A methodological guide to multiobjective optimization. Working Paper WP-79-122. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Wierzbicki, A.P. (1980) A mathematical basis for satisfying decision making. Working Paper WP-80-90. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Willoughby, A.H. (1969) The evolution of electric lamps. Lighting Research and Technology 1(2):77.

von Winterfeldt, D. (1975) An overview, integration, and evaluation of utility theory for decision analysis. Social Science Research Institute Research Report 75-9. Los Angeles, CA: University of Southern California.

von Winterfeldt, D., and G.W. Fischer (1975) Multiattribute utility theory: Models and assessment procedures. In: D. Wendt and C. Vlek (eds.), Probability and Human Decision Making, pp. 47–87. Dordrecht, Holland and Boston, MA: Reidel.

Yager, R.R. (1977) Subjective decision making. Proceedings of International Conference on Cybernetics and Society, Washington, DC, September, pp. 243–244. New York, NY: IEEE.

Zeleny, M. (1974) Linear Multiobjective Programming. New York, NY: Springer.

Zeleny, M. (1976) The theory of displaced ideal. Proceedings of Conference on Multiple-Criteria Decision Making, Kyoto, 1975, pp. 153–206. New York, NY: Springer.

Zeleny, M. (1980) Multiple objectives in mathematical progamming: Letting the man in. Computers and Operations Research 7:1–4.

Zellmer, G. (1980) Entscheidungstheoretische Aussagen zum Risiko und Möglichkeiten seiner Berücksichtigung bei der Vorbereitung volkswirtschaftlicher Bilanzentscheidungen (Statements from decision theory on risk and possibilities of its consideration in the preparation of economic budgeting decisions). Habilitation Thesis, University of Economics, Berlin (GDR).

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Collaborative Proceedings

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