WORKING PAPER

SUPPORTING TECHNOLOGY DEVELOPMENT EVALUATION WITH MULTIPLE ATTRIBUTE UTILITY ANALYSIS AND FUZZY DECISION ANALYSIS

Erkki Ormala

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PREFACE

The Management and Technology Area of IIASA always had an interest in the decision making process in organizations in general, and in decisions in particular. With the ever increasing complexity of technology and its impact as well as the attempts to support these decisions by new systems and schemes are increasing.

This working paper by Erkki Ormala, from the Finnish VTT research center is an attempt to briefly review the state-of-the-art of decision making support schemes and their applications. The suggestion of using two new techniques is worked out, namely, multiple attribute utility analysis and fuzzy decision analysis and applications of these techniques are described specifically focussed on technology development and evaluation as formulated in Finland.

This paper was written during the summer months (Erkki Ormala participated in the Young Scientists' Summer Program--YSSP) of 1982 and also contains the results achieved by the author in his home institute. The paper is recommended to those persons wanting quick information on this topic.

Tibor Vasko

Leader

Clearinghouse Activities

ABSTRACT

In many industrialized countries technology development programs have become one of the main policy measures for enhancing future economic growth. The choices between alternative programs have turned out to be highly unstructured decisions which are very difficult to support. In this study a process of evaluation system design is developed.

The approach developed disaggregates the problem into pieces. First, the objectives of the organization or activity have to be defined. Secondly, the properties of the objective set are analyzed using multiple attribute utility analysis and fuzzy decision analysis. The final system design starts with defining the required characteristics of the system. The system is composed of three separate subsystems interacting with each other. The prior evaluation system structures the prior evaluation process and defines the evaluation procedures, objectives, and responsibilities. The simulation model utilizing the mathematical theories

mentioned above supports the intuitive evaluation process. The performance evaluation system measures the performance of the organization, provides a check for the prior evaluations, and establishes a learning process in which the organization utilizes its own experience for orientation in the future.

The developed processes and systems are applied to the evaluation of technology development programs and projects at the Technical Research Center of Finland.

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SUPPORTING TECHNOLOGY DEVELOPMENT EVALUATION WITH MULTIPLE ATTRIBUTE UTILITY ANALYSIS AND FUZZY DECISION ANALYSIS

Erkki Ormala

1. INTRODUCTION

1.1 The Role and Impact of Technology Development

Future economic growth can no longer be based on an increasing utilization of the scarce means of production. Growth in productivity and an increased value added to products will contribute most to economic growth. This change in the ideology of growth will have many impacts on the economy and society in general. New process and product innovations can create economic growth under the new economic circumstances. Consequently, many countries have adopted new policies for enhancing the innovative capability of the economy. Yet there is little scientific evidence to support the existence of any goal-achievement relationships and verify the efficiency of innovation policies and measures (Goldberg 1981).

Many developed countries have, however, adopted policies and industrial strategies for strengthening international competitiveness on the grounds that technological development is the main contributing force behind the flow of new innovations, and hence behind a nation's technological superiority. A general recognition of the importance of technology development for the economy (see, for example, Freeman 1974; Blume 1981) has resulted in the formulation of technology development programs as an instrument of national economic policy.

In many big countries extensive public and private funds are being invested in the development of new technologies. Changes in the economic structure, however, cannot be very rapid because of the lack of resources, especially capital and skilled workers. Consequently, the main contributors to the national wealth in many countries will continue to be the traditional industries, at least until the end of this century. The competitiveness of the economy as a whole also requires development of the more traditional technologies.

The growing importance of technology development has created new problems and responsibilities for research and technology planners and executives, who must make important and difficult decisions about support for technology development programs. Selection of the best choice from among the alternatives and their mutual compatibility (Piatier 1981) will have tremendous impact on individual economies in the future. In big economies, wrong decisions may cause severe disturbances. In small ones, like the Finnish economy, they are even more critical. Because of the dearth of resources, only few programs can be supported and if too many of them fail, the resulting decline in economic competitiveness may plunge the country into a major economic crisis. Uncertainties about impacts and the inability to quantify them as well as deficiencies in the available methodologies further impede decision making about technology development programs.

This decision making process is more or less decentralized in most countries. Decisions are taken in governmental offices, individual companies, universities, and research institutions. They require careful consideration and deep understanding of the development of the economic environment and technology, the potentials of the economy, and available technical resources. The process of evaluating and selecting competing technology development programs is the topic of this study.

1.2 The Problem of Evaluation

Selection among technology development programs requires careful evaluation of the merits and drawbacks of the available alternatives. Despite many efforts in this direction, no generally accepted methodologies have been devised for evaluating technology development programs. This is mainly due to a crucial defect that differentiates, for example, the evaluation of technology development programs from capital budgeting (see Beattie and Reader 1971): the problem of measuring returns from investments in technology development. The U.S. National Science Board (1975) has summarized the results of studies of the measurement of the research and development performance. All of the studies found a common major limitation: the inability of conventional measures to capture the full impact of technology development on the economy and on society. Blake (1978) has concluded that decision makers are wasting their time when they try to directly relate technology development activities to profit or economic improvement.

All organizations and activities must have some purpose that justifies their existence. However, this purpose is most difficult to express in operational terms and usually only a vague qualitative statement is available. This lack of operationality in the formulation of the objectives of the activity is very true of technology development organizations.

On the other hand, the decision maker has at his disposal a set of more or less operationally defined program proposals. It is the decision maker's task to evaluate the proposals, measure their likely contribution to the purpose of the activity, and come up with a clear preference order among the alternatives: the gap between the general objective and the proposals must somehow be filled. For his evaluation he relies heavily on subjective judgment, managerial skills, and experience. The evaluation procedures may also be highly individual. This kind of decision making is very difficult to support with decision supporting systems or quantitative analysis. Yet the need for decision support is obvious and any true help would be most desirable.

1.3 The Approach of the Study

The evaluation of technology development programs is an extremely complex problem situation. The problem is socioeconomic as well as technological. It is multidisciplinary, dynamic, and highly unstructured. The history of research and development project selection and evaluation methods demonstrates clearly that no conventional or *ad hoc* methods have been generally accepted.

Two new mathematical theories, however, were developed in the 1970s and had reached a level of applicability by the end of the decade: the multiple attribute utility theory and the theory of fuzzy sets. These theories provide a suitable setting for modeling an evaluation of technology development programs.

This study, however, is not an exercise in mathematics or operations research; it is rather a systems analytic study where systems analysis is understood in its broadest sense.

> Many complex sociotechnical problems can be addressed by focusing scientific knowledge in appropriate ways by means of the logical, quantitative and structural tools of modern science and technology. The craft that does this is called applied systems analysis; it brings to bear the knowledge and methods of modern science and technology in combination with concepts of social goals and values, elements of judgment and skill, and appropriate consideration of the larger contexts and uncertainties that inevitably attend to such problems (IIASA 1981:217).

This study is being carried out partly at and for a technology development institution — the Technical Research Centre of Finland (VTT), a large multidisciplinary research institution. Consequently, the study focuses on evaluation problems faced by this kind of organization, but the approaches developed are also applicable to other organizations in the technology development "business."

One of the major problems in earlier work on R & D project evaluation and selection methods has been a tendency to underestimate the complexity of the problem and overlook organizational aspects as well as the subjective nature of the evaluation and to proceed directly to a complete prescription as to what the decision maker should do. This tendency is understandable but not acceptable. The analysts have tried to sell their projects to the decision makers by promising too much. The full prescription is beyond the possibilities of systems analysis today as far as the selection of technology development programs is concerned. The essence of systems analysis may be its ability to create a better and deeper understanding of the qualitative and quantitative aspects of the problem and through this better insight contribute to better decision making (see, for example, Keeney and Raiffa 1976; Keen and Scott-Morton 1978).

Every organization has its own characteristics, and decision procedures. Consequently, the results from studying the evaluation practice at a specific organization cannot be generalized. On the other hand, it is the purpose of a systems analytic study to assess this practice and possibly make some recommendations for improving it. In addition, if some feedback loops can be generated a learning process may be established. For example, if some system collects information about the completed programs and their impacts, the organization may be able to learn from its own experience and reorientate its operations accordingly.

1.4 The Objectives of the Study

The objectives of the study are defined in spirit in the preceding section. The study has two main objectives. One is to investigate possibilities for supporting unstructured managerial decisions by using the methods and tools of systems analysis. This objective ties the study closely to rapidly proceeding theoretical development in the fields of decision support systems and decision theory. The second general objective is to improve and support the evaluation and selection of technology development programs in general and at VTT in particular. This objective is more practical; it gives a clear development obligation to the study. These general objectives can be further subdivided into three lower-level objectives:

- to develop new systems analytic methods for evaluating technology development programs
- to construct a decision model that can be used for descriptive purposes as well as to some extent for prescriptive purposes
- to design an operational evaluation system for evaluating VTT's research work.

1.5 The Structure of the Study

This working paper is made up of eight chapters, which cover the theoretical development, and the description and some preliminary results of the empirical part. A more detailed description and the results of the empirical study will be reported later.

Chapter 1 is an introductory chapter in which the background, objectives, and structure of the study are presented. Chapter 2 reviews briefly present trends in the development of the descriptive and prescriptive modeling of decision making. Chapter 3 describes in detail the technology development process and develops conditions for modeling technology development evaluation. Chapter 4 presents the multiple attribute utility model. Special emphasis is given to setting objectives for technology development evaluation and to checking the conditions of independence which validate the different forms of the total preference function. In Chapter 5 the theory of fuzzy decision making and the foundations of fuzzy reasoning are presented.

In Chapter 6 a decision support system for technology development evaluation is developed. The system is based on the theories of multiple attribute utility theory and fuzzy decision making presented earlier.

Chapter 7 presents briefly an empirical study of posterior evaluation of VTT's research performance, the results of which are used to modify the general model applicable to the evaluation of VTT's programs. In Chapter 8 a short summary is presented and some conclusions are drawn.

2. ON THE MODELING OF DECISION MAKING

2.1 Prescriptive and Descriptive Models

Traditionally, models of decision making have been divided into two categories: prescriptive and descriptive models (Marschak 1964; Fishburn 1968; Kickert 1978). Prescriptive models are concerned with how decisions should be made. Traditional management science is strongly normative and its models are prescriptive. This normative perspective moves the decision marker towards identifying a clear objective, formalizing his objective function, and using the model that identifies the best choice in relation to this objective. Economic theory, within which the normative perspective has been developed, is not concerned with the decision process but with the logic of choice.

The descriptive tradition is concerned with how decisions are actually made. Descriptive models of the decision process based on behavioral research tradition stress the natural multiplicity of decision maker's objectives and values, the imprecision attached to their definition, and their inconsistent judgment. The main value of the descriptive counters to the rational ideal is their focus on the realities and constraints that must circumscribe any normative definition of optimality. In addition, they suggest that complex decision making is essentially marked by multiple criteria and subjective judgment and that decision makers are more concerned with reducing risk, and cognitive stress and conflict than with optimal solutions.

These two traditions have evolved quite apart from one another and not until recently has a third tradition been developed. This new approach synthesizes the concepts of the two earlier models and establishes a behaviorally grounded, analytic approach to the modeling of decision making (see, for example, Keen 1977).

2.2 Theories of Decision Making

Some recently published reviews (Keen 1977; Keen and Scott-Morton 1978; Sage 1981) describe the developments in decision making theory. A short summary of these reviews is presented here to provide a necessary base for the further subsequent chapters. The classification of the theories is from Keen and Scott-Morton (1978).

1. The rational manager view: This is the classic concept of decision making in organizations, developed from the microeconomic assumption of a rational, completely informed, single decision maker. Though heavily criticized in other contexts it retains a dominant influence in economic analysis.

2. The satisfying, process-oriented view: This approach, best known from H.A. Simon's work (1957; 1976; 1977) focuses on how a decision maker can most effectively use limited knowledge and skills. Heuristic rules of thumb are used for searching for solutions that are "good enough." The approach involves building a descriptive model of the decision process; the design goal is then to improve the existing solution.

3. The organizational procedures view: This concept seeks to understand decisions as the output of standard operating procedures invoked by organizational units. The emphasis in the model design is on discovering what these procedures are and how they might be supported or improved.

4. The political view: Decision making is seen as a personalized bargaining process between organizational units. Power and influence determine the outcome of any given decision.

5. The individual differences perspective: This perspective concentrates on the individual manager and his problem-solving and information-processing behavior. The focus is on the decision making style and on the background and personality of the manager.

Each of these theories has its own more or less well defined methodology (see, for example, Sage 1981).

This diversity of views on decision making clearly demonstrates the fact that no comprehensive, generally accepted theory of decision making has evolved so far. Intensive research has focused on synthesizing the different theories. Recent developments show that some models of decision making that have been developed within the frames of some specific theory incorporate ideas and aspects from other views of decision making. Zeleny's work (1975a; 1976; 1981) to develop "the theory of the displaced ideal" is an example of a combination of the rational view and the process view. Interactive decision models (Zionts and Wallenius 1976; Stewart 1981) and the models based on the reference point approach (Wierzbicky 1979; Kallio *et al.* 1980) are other examples of the synthesis endeavor.

2.3 Classifications of Decisions

Two important classifications of decisions are presented, since they form a simple basis for planning decision support. The first is that developed by Simon (1957; 1977). Decisions fall along a continuum ranging from highly structured to highly unstructured (also called programmed-nonprogrammed) with semi-structured in between. Structured decisions are routine and repetitive and their strategies (decision rules) can be externalized and modeled. Unstructured decisions are complex or elusive ones whose structure and strategies are difficult to perceive.

There is no clear borderline between the two classes of decisions and there has been a continuous evolution of decisions from unstructured to structured as the methodologies and knowledge of the decision making process have developed. Recent research on decision support has focused on the borderline problems, that is, on semi-structured decisions.

Another classification often used in decision support design is the Anthony taxonomy developed at the Harvard School of Business (see Keen and Scott-Morton 1978; Bonczek *et al.* 1981). The taxonomy is composed of strategic planning, management control, and operational control. Strategic planning refers to the process of deciding on the objectives of an organization, on changes in these objectives, and on the policies used to govern the acquisition, use, and disposition of resources. Management control is a combination of planning and control functions whereby managers assure that resources are acquired and utilized in an efficient and effective manner. Management control is constrained by the objectives and policies that result from strategic planning. Whereas management control requires judgment, operational control does not, since it is entirely governed by precisely defined decision rules.

There is also a continuum with operational control at one end, strategic planning at the other, and management control in the center. As one proceeds along the continuum from operational control through management control to strategic planning, the associated decisions become less and less structured; involving less control and more planning.

These two classifications together form a matrix for classifying decisions. In Table 1 the matrix is presented with examples of the decisions in each element of the matrix (Keen and Scott-Morton 1978:87).

Table 1. A framework for classifying decisions.

Type of Decision Task	Operational Control	Management Control	Strategic Planning
Structured	Inventory reordering	Linear programming for manufacturing	Plant location
Semistructured	Bond trading	Setting market budgets for consumer products	Capital acquisition analysis
Unstructured	Selecting a cover for Time Magazine	Hiring managers	R & D portfolio development

2.4 The Decision Maker

An important element in planning support for decision making is the notion of the decision maker. The following short description draws heavily on Keen (1977). Keen calls his decision maker an apprehensive man, whose decision strategies place immense emphasis on what has worked in the past. A heuristic is a rule of thumb based on experience. Such conservative strategies protect the individual against the common errors and strain caused by lack of analytic ability.

Man is not a good statistician. His performance is virtually always inferior to any simple linear regression model. He relies on heuristics, which are highly economical and usually effective, but which lead to systematic and predictable errors. He makes frequent errors in logic, but is generally able to rescue himself from his mistakes because of the self-correcting feedback of language.

Man lacks insight into his own values, and efforts to identify his preferences involve outside analysts' deducing them by some methodology. His behavior is markedly inconsistent. However, man is able to bypass his analytic we·' .ess. He can handle some immensely complex problems that he does not consciously understand. By focusing on small deviations from the status quo, the decision maker can avoid the need for formal evaluation. He will eschew the search for optimal solutions if this conflicts with his need for a sense of control and avoidance of complex computations of values and outcomes. His behavior is based mainly on the primacy of learning from past experience.

Apprehensive man is not a fool. He will use techniques that he can trust and validate within his own framework. He clearly needs methodologies that can extend his capabilities. In particular, he can surely benefit from any aid that reduces inconsistency, his most obvious weakness, improves his ineffective use of information, and encourages him to perform computations. Decision support should exploit his ability to resolve complex situational conflicts, to make effective decisions even where he lacks knowledge and understanding, and to balance the many interactions of means and ends involved in decision making.

2.5 Decision Support

The notion of decision support has developed from different origins, such as management information systems, operations research, and computer science. It is an essential tool in systems analysis. Some recent textbooks define its development and present status in detail (Keen and Scott-Morton 1978; Alter 1980; Gessford 1980; Fick and Sprague 1980;

Bonczek *et al.* 1981).

When planning decision support one has to take into account the notions described above: the purpose of the system, the theories of decision making, the nature of the decision, and the capabilities of the deci sion maker. A descriptive perspective is necessary to provide the basis for prescriptive design. To improve a decision process one must first define and analyze it (Keen and Scott-Morton 1978:61).

One has to be aware of the theoretical basis of the methodologies one plans to use in the systems design to be able to understand their implicit assumptions and limitations. Each theory and its methodologies can explain only a part of some complicated problem. In order to have more complete insight into the problem one has to use methodologies that can incorporate the ideas of more than one theory of decision making, or to carry out two or more independent studies each from a different point of view.

Different decision types require different kinds of support. Formal mathematical methods are usually applicable to structured operational control decisions. But as one moves towards unstructured strategic planning decisions, simple and easily comprehensible methods have to be adopted. The latter group of decisions is much more difficult to support; one may have to use some general problem solving techniques (Bonczek *et al.* 1981):

1) The use of analogy to find analogous, better known problems whose known solution strategies can be used to construct an analogous strategy for the problem.

2) The collection of additional information in order to redefine the decision problem.

3) Attempts to combine existing solution strategies to form a new strategy.

4) The use of intuition.

Also, the people involved in designing systems for unstructured decisions need to understand the specific managerial process of the decision problem much better than those building systems for structured decisions do. The processes through which they may contribute to better decisions are different. While systems for structured decisions may provide an optimal solution, systems for unstructured decisions tend to be means of learning and adaptation.

The designer of decision support should understand human abilities and weaknesses in general as well as the individual behavior, style, and personality of the decision maker confronted with the problem at hand.

In designing decision support, wide use is made of ideas and techniques from the areas of management science, data base management, formal logic, and linguistics. In the following chapters, these techniques together with the notions presented in this chapter are applied to the systems design for decision making related to the evaluation of technology development programs.

3. TECHNOLOGY DEVELOPMENT

There are many ways to classify research and development. The most commonly used categories are basic research, applied research, and development (see, for example, OECD 1979; 1981). However, this classification has turned out to be not very operational and consequently, other classifications have arisen, especially for technological research (see, for example, Hitch and McKean 1960; Ackoff 1970; Dean and Sengupta 1970; White 1975). Mark (1976) has proposed a tripartition into basic research, technology development, and development, corresponding approximately to the traditional classification, with applied research being replaced by technology development. Since technology development is somewhat more descriptive, it will be used here.

The process of technology development has the function of bridging the gap between basic research and development. It is important to define the technology development process for two reasons:

1. Technology development, which has become extremely important for economic growth, differs in many important respects from basic research and development, and in the past it has to a great extent been neglected by management science. Of the three, technology development may be the most difficult to manage, and yet most of the management literature has concentrated on problems of basic research or development.

2. The exponential growth of basic scientific knowledge has greatly increased the number of possible choices for new technology development. In the past, the rate of scientific progress was

such that technology developments were generally undertaken as a natural consequence of scientific discovery. Because of the increasing cost of technology development, it has simply become impossible to support all the possible technology developments that could be based on current scientific knowledge. But mechanisms for making choices regarding the initiation of new technological developments are still very rudimentary.

3.1 The Characteristics of Technology Development

Technology development basically means applying new technology to achieve certain practical ends. The characteristics of technology development can perhaps best be understood by comparing it with basic research and development. This section draws heavily on Mark's excellent presentation (1976).

The purpose of basic research is to find out why things happen the way they do in nature. The emphasis is always on the word "why." In contrast to basic research, development is a well defined activity whose purpose is to construct something new that will be useful to society. The primary question is therefore "how." In the process of technology development one takes newly developed scientific results and brings them to the point where they can be applied in engineering. In that sense technology development is closer to development than basic research, since it seeks to determine how new scientific principles can be applied to the solution of certain practical problems.

Basic scientific research is usually carried out by a small group of highly qualified people in an individual enterprise. Basic research is funded and encouraged primarily for cultural reasons. In contrast, development tends to be very highly interactive with society. The original purpose of the development project is to achieve some economic or political aim set by some decision maker outside the scientific or engineering profession. Development is a group activity involving designers, engineers, and managers. In contrast to basic research technology development is interdisciplinary in that a technology development program tends to involve a combination of several scientific disciplines. Thus technology development tends to be a group activity rather than an individual one. In contrast to development, the economics of the technology development process are poorly understood and it is generally not possible to base the decision for embarking on a new technology development program on purely economic grounds.

The time scale for application of the results of basic research is usually greater than ten years. In development, because of high economic expectations, the time scale is normally less than five years. The time scale for most technology development is somewhere between five and ten years. The amount of money necessary to carry out a technology development program tends to be greater than that needed for basic research but smaller than for a development project.

Basic research is carried out primarily at universities, whereas the industrial sector performs development activity to guarantee the necessary flow of new innovations. In most countries technology development is usually carried out by separate non-profit research organizations (technology development institutions) and financed jointly by the public and private sectors.

Finally, there is the question of quality control. In basic research, quality control is generally performed by the peers of the researchers. In development, quality can usually be measured by profit or some other socioeconomic measure. Of the three activities, the quality control of technology development is most difficult and methods for evaluating technology development are the least developed.

3.2 Evaluation of Technology Development

The problem of project evaluation and selection in basic research is fairly straightforward. Except for decisions concerning the total size of the basic research effort and its rough distribution over the disciplines, questions of project selection and evaluation are based entirely on the inner criteria of science and are strictly up to the scientists themselves.

Development projects should be evaluated and selected by measuring their usefulness, either in terms of profit or some other socioeconomic measure. In practice, however, it is rarely possible to assess precisely the values of these measures because of the many factors affecting the final result. The problem of evaluating development projects is a problem of measurement.

The problem of program evaluation in technology development is the most difficult of the three evaluation problems. While scientific attractiveness is the guide for choosing basic research projects and profit is the main criterion for selecting development projects, there is no clear guiding factor for the selection of technology development programs. Often although the whole effort is aimed toward the application of scientific results, at the point in time when the selection is made, the application may not yet be apparent. The given objectives are often loosely defined and tend to be qualitative, sometimes contradictory and interrelated. The problem of evaluation is not only one of measurement, but also one of a lack of operational objectives and precisely defined constraints. The evaluation of technology development is a multiobjective problem involving a substantial amount of subjective judgment. Academic research on basic research has tended to be the domain of sociologists while the attention of economists and management scientists has generally gravitated toward the development end of the spectrum. Technology development has not attracted the attention of any research discipline.

3.3 R & D Evaluation Methods

During the last thirty years numerous R & D evaluation and selection methods have been developed. Many reviews in which the properties and conditions of these methods are assessed can be found in the literature (Cetron *et al.* 1976; Souder 1973; Sveriges Mekanförbund 1973; Baker 1974; Baker and Freeland 1975; Ormala 1980; Haustein and Weber 1980; Winkofsky *et al.* 1980).

There are two primary categories of models (Baker and Freeland 1975): 1) benefit measurement models and 2) project selection models.

The benefit measurement models are further divided into:

1. Comparative methods in which a knowledgeable person (or persons) compares one proposal either with another proposal or with some subset of alternative projects.

2. Scoring models in which each proposal is given scores reflecting how well it meets the desired characteristics on some scale. Sometimes the scores are combined by addition or multiplication to produce an overall benefit measure.

3. Benefit contribution methods in which one examines how well a proposal satisfies the basic objective of the activity.

The selection methods vary from simple ranking and one-constraint (e.g., budget) cases to complicated multiple-objective optimization problems.

In another approach to constructing R & D evaluation and selection models, instead of looking at each individual proposal separately, one evaluates the whole set of proposals together with the proceeding projects. Portfolio models attempt to optimize some value function and are subject to the fact that the organization is operating in a constrained environment (Gear 1974; Winkofsky *et al.* 1980).

Studies of present practices in using R & D evaluation and selection methods (see for example Mansfield *et al.* 1971:48-49; Andren 1973; Clarke 1974; Freeman 1974:178; CEC 1979b; Winkofsky *et al.* 1980) show that systematic methods are used fairly often, especially in a business environment. However, it is difficult to say how much the methods being used actually contribute to the final decision and how much they are used as window dressing, the real determinants of selection being at work behind the facade (Mansfield *et al.* 1971). The methods are used mainly to evaluate development projects, where economic assessments seem to dominate.

Knoppers (1979) has concluded that in an attempt to become more sophisticated in their decision making, managers turned increasingly to more complex methodologies and when these were ultimately found wanting, they returned to simpler models. A short review of the methods used in industry (see Collier 1977; Winkofsky *et al.* 1980; Wolff 1980; Keaton 1980; Becker 1980) supports Knoppers' findings.

Most of the R & D project selection and evaluation models that have been developed still seem to possess several limitations, among them (Baker and Freeland 1975):

1) inadequate treatment of risk and uncertainty
2) inadequate treatment of multiple, often interrelated criteria
3) inadequate treatment of project interrelationships
4) no explicit incorporation of the experience and knowledge of the R & D manager
5) inability to recognize and treat nonmonetary aspects
6) perceptions held by the R & D managers that the models are unnecessarily difficult to use and understand
7) inadequate treatment of the time variant property of data and criteria.

The trend in general decision support methods towards supporting more and more unstructured decisions has narrowed the gap between the general decision theory and R & D evaluation. In the future, R & D evaluation methods will become merged with methods supporting unstructured and semistructured decisions. On the other hand, Winkofsky *et al.* (1980) propose that if R & D evaluation is to be enhanced by the use of models, the model builders must begin to adapt their models to existing organizational processes.

3.4 The Premises for the Support of Technology Development Evaluation

Despite the abundance of R & D evaluation models presented in the literature, little is said about the evaluation of technology development. Most of the models presented are designed to support the evaluation of development projects and are less applicable to research evaluation. Scientific indicators, peer methods, and some methods for the evaluation of research groups have been developed for evaluating basic research (see, for example, Stolte-Heiskanen 1979; Martin and Irvine 1980).

Some guidelines for designing support technology development evaluation have, however, been proposed. CEC's R & D evaluation conference (1979a) stressed the importance of past experience, careful formulation of objectives and the uniqueness of each technology development evaluation problem. Also, the dangers of strictly numerical methods were warned against. Blake (1978:65) and Pokropp (1979) conclude that in order to produce consistent and reliable evaluations, an explicit evaluation system should be designed and implemented. Lane *et al.* (1981) have studied the management of large research and development programs. They stress the importance of establishing a learning process in which the responsible management and organization can learn from its own experience. Evaluation should be integrated into the technology planning process as a routine procedure (OECD 1972).

The evaluation of technology development programs is an unstructured, strategic planning decision process. Consequently standard decision models seem inappropriate for its support. Rather, some of the general problem solving methods presented in Section 2.5 should be adopted.

Any system designed to support technology development evaluation should aid the decision maker in overcoming two of his most obvious weaknesses: his poor statistical ability and the inconsistency in his logic.

The need for clear research objectives has been strongly emphasized in the literature (see, for example, CEC 1979a; Deshmukh and Chikte 1980; Winkofsky *et al.* 1980). The formulation of research objectives is vitally important, because:

1. They tie the research function closely to the objectives of the organization;
2. They help to convey the strategy defined by the top management of the organization to lower levels in an operational form;
3. They form the basis for decision making in different parts of the organization.

Research objectives cannot be a standard set of objectives suitable for all research organizations (Winkofsky *et al.* 1980:186). The set of objectives must be tailored specifically to each organization, taking into account its purpose and nature.

Because the process of technology development evaluation is multiobjective in nature, (Winkofsky *et al.* 1980:186), any model designed to support technology development has to be able to deal with multiple objectives. Although the importance of research objectives is generally recognized; and although scholars (Radnor and Rich 1980:114) typically include the objectives in initial models, this usually diffuses away during the course of the studies.

Technology development is a highly creative activity whose evaluation is a complex process requiring substantial subjective judgment and managerial experience. A model can only explain a part, often only a fraction of the evaluation process. Consequently any system incapable of incorporating subjective judgment is inadequate.

Finally, there is the question of the purpose of the evaluation. In the literature prior and posterior (or *ex ante* and *ex post*) evaluations have often been strictly separated (CEC 1979a). However, these two types of evaluations are highly interlinked. It is a well-established principle that decision making for basic and applied R & D should be supported by a performance evaluation system (Blake 1978:65). Posterior evaluation produces information on the performance of the organization and provides a rough means for checking the validity of the prior evaluations.

4. MULTIPLE ATTRIBUTE UTILITY THEORY

The basic concepts of expected utility theory were originally formulated by von Neumann and Morgenstern (1947). They were further developed by Luce and Raiffa (1957), Raiffa (1968), Fishburn (1970), Keeney (1974), and Keeney and Raiffa (1976), among others.

4.1 Single-Objective Decision Making

The basic formulations of one-attribute utility model can be found in Raiffa (1968) and Keeney and Raiffa (1976).

Let A be a set of possible actions and X a set of consequences of these actions. $a_j \in A$ ($j = 1,\ldots,m$) are the elements of A and $x_j \in X$ are the elements of X. The elements of X are distinct consequences within X and are mutually independent. It is known precisely which action will lead to which consequence. In other words there exists a relation $R \subset A \times X$, which indicates that if $(a_j, x_j) \in R$, then x_j will be the consequence of action a_j. Furthermore the decision maker has an order of preference within X, which is represented by a value function $v(x)$, with the property:

$$\forall a_j, a_k \in A \quad \exists v(x_j), v(x_k) \tag{1}$$

so that a_j is preferred to a_k ($a_j \succ a_k$) if and only if $v(x_j) > v(x_k)$. In this model the decision maker will decide to take the action a_j that gives him the highest value of $v(x)$. This deterministic case is called decision making under certainty.

If each action has a set of possible consequences and the probabilities of these consequences are known, decision making is said to be under risk. Let P be the set of probability distributions on X. The elements of

$P(p_j \in P)$ are non-negative, real-valued functions on X such that $\int_x p(x)dx = 1$. For each $a_j \in A$ there is $p_j(x) \in P$ that defines the probability distribution of the consequences of the action of a_j. The relation between the actions and the consequences is of the form: $R \subset A \times P$.

Risky actions can be ordered by using the expected utilities of their probabilities if certain axiomatic requirements are satisfied (see, for example, Luce and Raiffa 1957). The utility function is generated by comparing certainty option to risky option or gamble, which is to receive a certain consequence value (the best x^*) with probability λ and another (the worst x^0) with the complementary probability $1 - \lambda$.

$$x_j \sim \lambda_j x^* + (1 - \lambda_j) x^0 \tag{2}$$

The λ-values that satisfy the indifference equation can be used to numerically scale the x_j's. The fundamental result of utility theory is that the expected values of λ's can be used to numerically scale probability distributions on X.

The utility function can be generated from the λ_j-values by positive linear transformation and they are usually scaled from 0 to 1.

The preference ordering in P is represented by the expected utilities of the probability distributions p_j. These yield further the order of preference in A:

$$\forall a_j, a_k \in A \exists \int_x p_j(x) u(x) dx, \int_x p_k(x) u(x) dx \tag{3}$$

so that

$$a_j \succ a_k \Leftrightarrow \int_x p_j(x) u(x) dx > \int_x p_k(x) u(x) dx \tag{4}$$

The assessment and properties of the utility functions and expected utilities are presented in detail in Raiffa (1968).

4.2 Decision Making with Multiple Objectives

In most real world decision situations more than one objective have to be considered. The requirement of including a number of objectives has resulted in the development of the multiple attribute utility theory in the 1960s and 1970s (see, for example, Fishburn 1970; MacCrimmon 1973; Keeney and Raiffa 1976; Hwang and Masud 1979).

In multiple attribute utility theory each objective is measured in terms of some attribute. The set of attributes defines a rectangular, finite-dimensional Euclidean consequence space. The set of possible actions (A) is defined as above. The set of consequences of the actions is a subset in the consequence space. The consequence set (X) is a Cartesian product of the consequence sets ($X = X_1 \times X_2 \times \ldots\ldots \times X_n$) and it includes all the n-tuples $[(x_1, x_2, \ldots, x_n); x_i \in X_i; (i=1,\ldots,n)]$

A consequence of an action is no longer a scalar but a vector consequence $\bar{x}_j = (x_{1j}, x_{2j}, \ldots, x_{nj})$. The relation R that represents the mapping from the action set to the consequence set is of the form $R \subset A \times X; [a_j, (x_1, x_2, \ldots, x_n)] \in R, \forall j$. Similar formulations can also be written for the risky case, where the consequence set is a set of probability distributions.

In the model the decision maker's preference structure is represented by a total preference function (value function or utility function).

$$U(\bar{x}) = G(x_1, x_2, \ldots, x_n) \tag{5}$$

This function can in some special cases be expressed as a function of one variable preference functions

$$U(\bar{x}) = F[u_1(x_1), u_2(x_2), \ldots, u_n(x_n)] \tag{6}$$

where F is a scalar valued function and u_i a utility function over X_i.

In the model decision making is composed of a three phase process that is presented in Figure 1.

In the multiple attribute utility model, value function and utility function are vector functions with forms similar to those presented in the single-objective case.

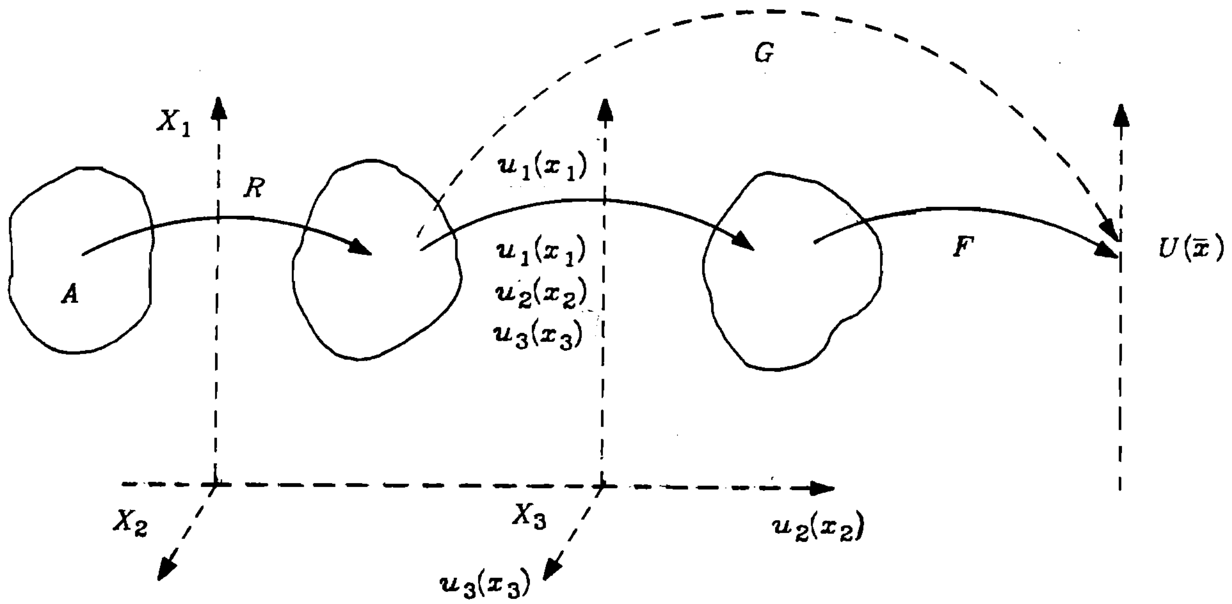


Figure 1. A three phase decision making process in the multiple attribute utility model.

4.3 Objectives and Attributes

The structuring of objectives forms the basis for the modeling process. Generating the objectives is an unstructured strategic planning decision and there is no single right way to support this decision. A natural way, however, is to construct an objective hierarchy starting from the expressed purpose of the organization. This often qualitative statement can be subdivided into objectives and these further into lower level objectives in more operational terms. The lower level objectives clarify the intended meaning of the higher level objective. The lower level objectives can also be thought of as the means to the end, the end being defined by the higher level objective. The process of constructing an objective hierarchy is iterative and highly intuitive. A hypothetical example of an objective hierarchy is presented in Figure 2.

An objective hierarchy is a useful instrument for evaluating possible actions. From the objective hierarchy a proper set of objectives can be chosen to be used as objectives in the multiple attribute utility model. The objective set structures the consequence set by defining an Euclidean

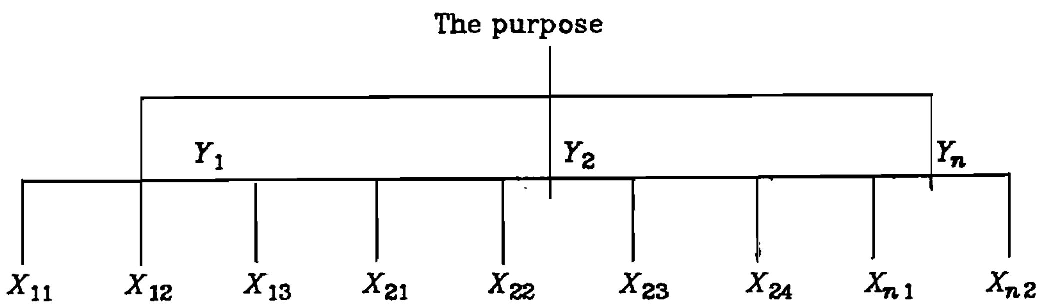


Figure 2. A hypothetical example of an objective hierarchy.

space including the consequence set. This structuring makes it possible to evaluate the consequences of the alternatives within a comprehensible frame of reference.

In the evaluation one has to be able to measure the objectives. These measures are called attributes and they have to be comprehensive and measurable (Keeney and Raiffa 1976). The attribute scales may be objective or subjective. Objective scales are preferable because of the deficiencies of the subjective scales (Ormala 1980).

The objective hierarchies as defined by different decision makers are not always alike. They reflect the decision makers' understanding of the purpose and objectives of the organization. There is always a subjective element involved in the structuring process. Comparisons between differing hierarchies may give important information about differing perceptions of the objectives. Some discrepancies may have to be accepted, but obvious disagreement should be negotiated to cohere perceptions.

The chosen attribute set has to have certain properties to be appropriate for the model (Keeney and Raiffa 1976:50-52). It must be:

1) *complete*, to cover all the important aspects of the problem
2) *operational*, to be used meaningfully in the analysis
3) *decomposable*, to simplify the evaluation process and to break it down into parts
4) *nonredundant*, to avoid duplication in counting
5) *minimal*, to keep the problem reasonably small

Finding the right objectives and attributes is crucial — even more important than finding the very best alternative. The wrong objectives mean the research is devoted to the wrong problem; selecting a slightly inferior alternative is not nearly so serious.

4.4 Independence Concepts

After the attribute set has been generated, the problem arises of how to assess the preference order of the actions with the help of the attribute set. In multiple attribute utility model the independence properties of the attribute set validate the simple forms of the total preference function yielding the required preference order. The independence conditions have been developed by Fishburn (1970; 1977), Keeney (1974), Fishburn and Keeney (1974), Keeney and Raiffa (1976).

Let $X = \{X_1, X_2, \ldots, X_n\}$ be the attribute set and $X_{\bar{i}}$ the complement set of X_i ($X_i \cup X_{\bar{i}} = X$).

Additive independence (AI) (Fishburn 1970): Attributes $X_1, X_2, \ldots, X_n$ are additive independent if preferences over lotteries on $X_1, X_2, \ldots, X_n$ depend only on their marginal probability distributions and not on their joint probability distributions.

Utility independence (UI) (Keeney 1974; Keeney and Raiffa 1976): Attribute X_i is utility independent of its complement $X_{\bar{i}}$ if the conditional preference order for lotteries involving only changes in the values of X_i does not depend on the values of other attributes when they are held fixed.

Preferential independence (PI) (Keeney 1974; Keeney and Raiffa 1976). The subset $\{X_i, X_k\}$ of the whole attribute set X is preferentially independent of its complement set $\{X_i, X_k\}-$, if the preference order in the values of $\{X_i, X_k\}$ does not depend on the values of $\{X_i, X_k\}-$ that are held fixed.

4.5 Some Simple Total Preference Functions

If the attributes are utility independent of each other there is a single utility function over each X_i. The preferences for varying values of X_i can be assessed after fixing the values of $X_{\bar{i}}$ at convenient levels. The conditional utility function $u_i(x_i)$ over X_i does not depend on the value of $X_{\bar{i}}$.

By linear transformation all the unidimensional conditional utility functions can be scaled from 0 to 1. Because of the scaling of the utility functions the original scales describing the importance and the range of the attribute values have to be taken into account by using positive scaling factors (k_i). Consequently the total utility function is a function of n unidimensional conditional utility functions and n + scaling factors.

The presented independence properties of the attribute set define the form of some of the most important total preference functions.

Additive value function (Fishburn 1970; Krantz ***et al.*** 1971). In the certainity case the total value function is additive

$$v(x_1, x_2, \ldots x_n) = \sum_{i=1}^{n} k_i v_i(x_i) \tag{7}$$

where $v_i(x_i)$ is a unidimensional value function over X_i, if and only if every subset of X is preferentially independent of its complementary set.

Additive utility function (Fishburn 1970; Keeney and Raiffa, 1976). With risky consequences the total utility function is additive:

$$U(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} k_i u_i(x_i) \tag{8}$$

if and only if the attributes are additive independent.

Multiplicative utility function (Keeney 1974; Keeney and Raiffa 1976). The total utility function is multiplicative:

$$KU(\bar{x}) + 1 = \prod_{i=1}^{n} [Kk_i u_i(x_i) + 1] \tag{9}$$

if and only if every subset of X is utility independent of its complement. K is an empirical constant.

Multilinear utility function (Keeney and Raiffa 1976). The total utility function is multilinear (written for $n = 3$):

$$\begin{aligned} U(\bar{x}) = {} & k_1 u_1(x_1) + k_2 u_2(x_2) + k_3 u_3(x_3) + k_{12} k_1 k_2 u_1(x_1) u_2(x_2) \\ & + k_{13} u_1(x_1) u_3(x_3) + k_{23} k_2 k_3 u_2(x_2) u_3(x_3) \\ & + k_{123} k_1 k_2 k_3 u_1(x_1) u_2(x_2) u_3(x_3) \end{aligned} \tag{10}$$

Also many other forms of the total preference functions have been presented in the literature (see for example Fishburn 1970; Krantz *et al.* 1971; Fishburn and Keeney 1974; Farquhar 1977; Bell 1977; Hemming 1978), but the forms defined above are the most important and also the most commonly used. The necessary and sufficient independence conditions can be modified to other sets of conditions that may be more feasible in some applications (Keeney and Raiffa 1976).

4.6 Scaling Factors

The scaling factors (k_i) are empirical constants. The basic idea in assessing the scaling factors is to obtain a set of independent indifference equations with as many unknowns, which are then solved to obtain the k_i values. These equations can be generated from certainty considerations, probabilistic considerations, or a combination of both.

It is important to interpret the meaning of the scaling factors correctly. They reflect in a way the relative importance of the attributes, but they are also functions of the ranges of the attribute values in the current decision situation. If the ranges will change all the scaling factors will also change. Consequently the scaling factors do not describe the importance of the attributes in general but the relative importance in the present decision situation.

The empirical constant K of the multiplicative utility function (5) reflects the mutual dependence of the attributes. If $K = 0$, the utility function is additive and there is no interaction of preference between the attributes. But if $K < 0$ the attributes are substitutes and if $K > 0$ they complement each other (see for example Keeney and Raiffa 1976).

4.7 Multiple Attribute Utility Theory as Decision Support

Multiple attribute utility theory is a strong and sophisticated mathematical theory (see Fishburn 1970). However, in most real world applications many problems and suspicions arise.

Already the attributes and the attribute set may be a source of many problems. The property requirements of the attributes (measurability, comprehensiveness) may be difficult to fulfill. Usually the consequences are not in a natural multiattribute form. Then it is important to identify the most important aspects of the consequences and to structure X accordingly. The initially unstructured problem can, of course, be recast into a multiattribute formulation in many ways, and some effort is required to obtain a formulation that reflects the most important features of the consequences (Fishburn 1977:176). Strictly speaking the n-tuple vector description is not identical to the original consequence. It is only a subjective approximation of the real consequence. There is no objective way to reveal the differences, which may cause considerable bias.

The requirement for non-redundancy in the attribute set may be especially difficult to satisfy. If there is enough statistical data from earlier decisions, correlations between the attributes should be calculated. The presence of significant correlations may indicate that redundancies exist. They should be eliminated by transforming the attribute set. This can be done by using for example factor analysis to generate a new orthogonal attribute set. These new attributes may, however, be meaningless to the decision maker and consequently useless (see Easton 1973). Other possibilities are to replace the correlating criteria pairs with some proxy attribute or, if the correlation is very high, to reject one of the attributes and use only the other in the analysis (Keeney and Raiffa 1976).

Multiple attribute utility theory assumes that decisions are taken by maximizing expected utility. In economic and psychological literature there is clear evidence that this is not always the case (Tversky 1977; Slovic *et al.* 1977; Sage 1981). The theory is based on rather strong assumptions concerning rational behavior (see Section 2.2) and some recent developments (see for example Zeleny 1976, 1981; Wierzbicky 1979; White and Sage 1980) provide alternate approaches. The process of generating the utility functions is difficult and laborious. Even determining the simpliest (additive) total utility function demands at least $n + n\,(m + 2)$ assessments (Sarin 1977). Independence and consistency checks demand many more assessments in addition.

The most important concern of the multiple attribute utility theory have not been real life decision making problems but rather formal considerations on the form of aggregation and testing of the applicability of the model (see Starr and Zeleny 1977; Haustein and Weber 1980).

It is extremely difficult to test the independence conditions (Haustein and Weber 1980) because

- there is a lack of efficient test procedures
- testing is impossible for all data
- questions for validity tests are impossible to answer, i.e., the decision maker is unable to make the necessary judgments.

If the conditions are violated or impossible to test, some approximations or other methods have to be adopted. (This question will be discussed in Section 4.8).

One severe limitation of utility theory as decision support is that it has no direct connection to any other theory that could validate the utility functions. The decision maker's utilities are all that count. This also leaves room for speculations. The decision maker may try to manipulate his statements in order to use the analysis for advocating purposes. The analyst has no way to reveal these speculations if the statements are consistent.

All the above mentioned problems present severe limitations to the use of multiple attribute utility theory as decision support. However, many successful applications have also been reported (see for example Cochrane and Zeleny 1973; Zeleny 1975b; Bell *et al.* 1977; Zionts 1977). But despite its many problems the rational model is invaluable in that it can often be used as a reference for comparing actual behavior with ideal normative behavior. Further, it provides a benchmark against which to compare simplified heuristics (Sage 1981).

In technology development evaluation, the role of the multiple attribute utility theory is very interesting, although only very few direct applications have been reported (see Keefer 1978; Vari and David 1982; Vescenyi 1982), but as can be shown, many simple *ad hoc* methods developed for R & D evaluation are rough approximations of the attribute utility model (Ormala 1980). Especially when the purpose of the analysis is to increase understanding of the objectives and to study the properties of the attribute set, rather than to determine the optimal course of action, multiple attribute utility theory provides an invaluable tool for the analysis.

4.8 Dependent Attributes

If the attributes are dependent or the independence conditions can not be tested, the following approaches can be exploited.

1. Transform the attribute set (see Section 4.7)

2. Assess the total preference function directly over the whole consequence space (Keeney and Raiffa 1976). This solution, however, is impossible in practice when there are more than two attributes involved.

3. Use the general functions regardless of violations of the conditions. Empirical studies have confirmed that people tend to use the additive form in aggregating the attributes (Goldberg 1971; Haustein and Weber 1980). Humphreys (1977) discusses options to be taken in applications where assumptions do not hold and states that most violations do not seem to be of critical importance for the validity of the solutions obtained.

4. Use mathematical approximation. Fishburn (1977) proposes using the multiplicative-additive form:

   $$U(\bar{x}) = \sum_{j=1}^{m} f_{1j}(x_1) f_{2j}(x_2) \cdots f_{nj}(x_n)$$

   However, very seldom are the necessary numerical data available for the approximation.

5. Use some other approach to investigate the decision maker's preference structure. Larichev (1977; 1982) has developed a new technique for evaluating technology development proposals using only natural language statements. Other approaches are to use the tools of formal logic (Bonczek *et al.* 1981), artificial intelligence (Newell and Simon 1972) or fuzzy decision theory (Kickert 1978). Of these three theories the fuzzy decision theory seems best suited in dealing with unstructured decisions

with uncertain data.

5. FUZZY DECISION MAKING

Fuzzy decision making is based on the theory of fuzzy sets established by Zadeh (1965). The theory is a natural extension of the traditional Boolean theory of sets (see Gaines 1977; Kickert 1978).

Let E be a set (often called reference set or universe set) and A a subset of E. If an element of E also belongs to A, this membership is indicated by a two-valued characteristic function ($\mu_A(x)$) that may have a value equal to zero or one. Fuzzy subset is a set whose characteristic function may take any value whatsoever in the closed interval $[0,1]$. Formally, a fuzzy set can be defined as follows (see Kaufmann 1975).

> Let E be a set and x be an element of E. Then a fuzzy (sub-)set A of E is a set of ordered pairs $\{(x,\mu_A(x))\}$, $\forall x \in E$, where $\mu_A(x)$ is a membership characteristic function, that gets its values in a totally ordered set M (= closed interval $[0,1]$) and which indicates the degree of membership.

If $M = \{0,1\}$ the set is a nonfuzzy Boolean subset and the function $\mu_A(x)$ is a binary characteristic function.

5.1 Basic Operations on Fuzzy Sets

The basic operation of the Boolean theory of sets have their equivalences on fuzzy sets. Let E be a reference set, and let A and B be two fuzzy subsets of E defined as above. The most important operations on fuzzy sets are the following (see for example Bellman and Zadeh 1970; Kickert 1978):

Inclusion: A is included in B $(A \subset B)$ if

$$\mu_A(x) \leq \mu_B(x) \quad \forall x \in E \tag{11}$$

Equality: A and B are equal $(A = B)$ if

$$\mu_A(x) = \mu_B(x) \quad \forall x \in E \tag{12}$$

Complementation: A and B are complementary $(A = \bar{B})$ if

$$\mu_A(x) = 1 - \mu_B(x) \quad \forall x \in E \tag{13}$$

complementariness corresponds to the notation "not."

Intersection: the intersection set of fuzzy sets A and B $(A \cap B)$ is defined by

$$\mu_{A \cap B} = \min(\mu_A(x), \mu_B(x)), \quad \forall x \in E \tag{14}$$

Union: the union set of two fuzzy sets A and B $(A \cup B)$ is defined by

$$\mu_{A \cup B} = \max(\mu_A(x), \mu_B(x)), \quad \forall x \in E \tag{15}$$

Often min and max operators are replaced by the conjunction symbol $\wedge$ and the disjunction symbol $\vee$. The notion of intersection bears a close relation to the notion of the connective "and" and union to the connective "or." If some algebraic weaknesses are accepted intersection and union can be defined as the algebraic product and sum of the membership functions of A and B (Kaufmann 1975):

$$\mu_{A \cap B} = \mu_A(x) \cdot \mu_B(x) \text{ and} \tag{16}$$

$$\mu_{A \cup B} = \mu_A(x) + \mu_B(x) - \mu_A(x)\mu_B(x) \tag{17}$$

The question of the "right" forms of union and intersection are of great importance in approximate reasoning when connectives "and" and "or" are approximated (see the discussion in Section 5.3).

5.2 Fuzzy Multiple Objective Decision Making

Fuzzy decision making was first introduced by Bellmann and Zadeh (1970), who also proposed a procedure for solving fuzzy multiple goal ($G_1,\ldots,G_n$) and constraint ($C_1, \ldots, C_K$) decision problems. Their solution was to define a fuzzy decision as a fuzzy set (D) resulting from the intersection of fuzzy goals and constraints:

$$D = (\bigcap_{i=1}^{n} G_i) \cap (\bigcap_{k=1}^{K} C_k) \tag{18}$$

Zimmermann (1975; 1978) has extended the model by using linear programming. Yager (1978; 1981) has further extended the model to allow for objectives of differing importance. The degrees of importance can be expressed in quantitative or linguistic form. The model that uses linguistic input is based on the reformulation of fuzzy implication (see Section 5.3) and has the form (Yager 1981):

$$D = \bigcap_{i=1}^{n} (\bar{B}_i \cup G_i) \tag{19}$$

where $\bar{B}_i$ is the fuzzy complement of the fuzzy set corresponding to the linguistic weight of the goal G_i.

The rule of choice in the presented models is to find the action that best satisfies the goals. That is the action j that maximizes the membership function $\mu_D(x)$.

Another approach to fuzzy multiple objective decision making is based on the principle of fuzzifying mathematical structures (see for example, Baas and Kwakernaak 1977; Gaines 1977; Dubois and Prade 1980:281-283). In this approach the form of the preference function is known but the values of the attributes cannot be assessed in deterministic or probabilistic form. In most cases the attribute values are linguistic variables that can be defined as fuzzy sets. The procedure to generate a fuzzy set induced by a mapping provides a proper means to assess the total utilities.

Let G be the total preference function $(G : X_1 \times X_2 \times \ldots \times X_n \rightarrow U)$. Let B_{ij} be the fuzzy set of alternative j on X_i. For each alternative a fuzzy set C_j in U can be assessed by the function

$$\mu_{C_j}(U) = \sup_{x_1, \ldots, x_n : G(x_1, \ldots, x_n) = U} \bigwedge_{i=1}^{n} \mu_{B_{ij}}(x_i) \qquad (20)$$

The fundamental change compared to classical analysis is to replace the precise concept that a variable has a value with a fuzzy concept that a variable has a degree of membership to each possible value.

The formula (20) actually means that with each possible value of the argument of the function is associated a degree of membership that is the lowest of the degrees of membership of each of its components; and with each possible value of a result of the function is associated a degree of membership that is the highest of those of all the arguments giving that value (see Gaines 1977:37).

The result of the analysis is a set of fuzzy sets $(B_1, \ldots, B_j, \ldots, B_m)$ on U (see Figure 3).

Now the question arises of how to assess the preference order between the alternatives by using the corresponding fuzzy sets (B_j). The

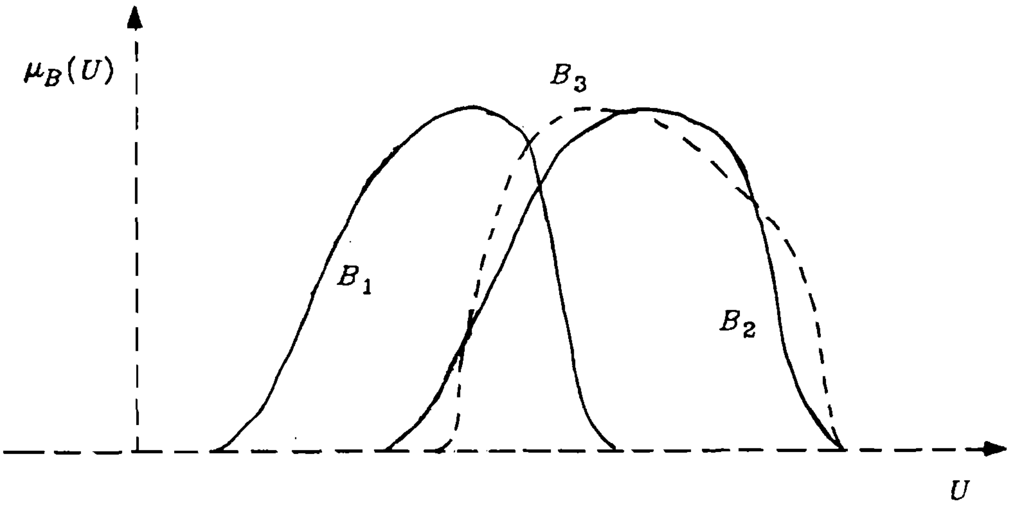


Figure 3. Three induced fuzzy sets (B_1,B_2,B_3) on U.

available information and the decision procedure may be fuzzy; the required actions are not. The concept of fuzziness incorporates vagueness into the analysis as an independent variable. The preference order is dependent not only on the total utility of each alternative but also on the vagueness attached to it. However, in may cases the choice is obvious. For example in Figure 3, B_2 fuzzily dominates B_1 and is consequently strictly preferred to B_1 (see Freeling 1980). If one has to compare B_2 to B_3 many problems arise and also the proposed solutions (see for example Baas and Kwakernaak 1977; Jain 1977; Watson *et al.* 1979; Tong and Bonissone 1980) are complicated and less convincing.

All the proposed procedures, except fuzzy dominance, seem to raise questions about their validity and in some cases no unique preference order can be assessed.

5.3 Approximate Reasoning

If the form of the preference function is not known and no predetermined min-max-type rules seem adequate, one has to go further and try to approximate the decision maker's preference structure by using the rules of approximate reasoning.

Formal logic is commonly used to determine information processing strategies that are appropriate for a given problem (Bonczek *et al.* 1981). Approximate reasoning is an extension of formal logic. Actually approximate reasoning can be defined as reasoning with vague statements and it is clear that human approximate reasoning is very strongly related to the typical form of vagueness: the linguistic form. Fuzzy algebra provides a formal basis for linguistic synthesis (Baptisella and Ollero 1980).

Linguistic variables are variables that can be described with fuzzy sets and whose values are not numbers but words or sentences in a natural or artificial language (Kickert 1978). Linguistic variables are very often constructed from some primary terms by means of connectives such as "and" and "or," the complementation "not" and the so-called hedges: very, rather, more or less, etc. which all have their respective mathematical formulations (see Gaines 1977; Kickert 1978).

Five additional concepts have to be defined to provide the necessary rules for appropriate reasoning (Bellman and Zadeh 1970; Zadeh 1973; Kickert 1978).

Fuzzy relation: A binary fuzzy relation R from a set X to a set Y is a fuzzy set on $X \times Y$ defined by $\mu_R(x, y)$.

Cartesian product of fuzzy sets: The Cartesian product of fuzzy sets A on X and B on Y is defined by

$$\mu_{A \times B}(x,y) = \min[\mu_A(x), \mu_B(y)] \tag{21}$$

Implication: Fuzzy implication "if A then B ($A \Longrightarrow B$) is equal to fuzzy Cartesian product (21).

Compositional rule of inference: Let A be a fuzzy set on X and B on Y and R a fuzzy relation on $X \times Y$,

$$\mu_B(y) = \max_x \min[\mu_A(x), \mu_R(x,y)] \tag{22}$$

This rule supports the reasoning where there exists a relationship R and an implicant A and the implied result B. Usually the fuzzy sets are linguistic variables. However the resulting fuzzy set B generaly will not coincide with an element of the set of possible linguistic values. Consequently the linguistic value closest to B has to be assigned to it.

When the fuzzy relation of the compositional rules of inference is replaced by fuzzy implication, fuzzy *modus ponens* is defined (see Kickert 1978:125). The compositional rule of inference and the fuzzy implication together with linguistic variables provide a means for approximating the decision maker's preference structure. The concepts of fuzzy reasoning are used to convert heuristic decision rules as expressed by the decision maker into a formal model, which in a sense is nothing other than a linguistic model of the decision making process.

The right forms of connectives (see Section 5.1) have been discussed in the literature (see Gaines 1977; Zimmermann and Zysno 1980; Yager 1981). Neither of the "and" operations implies that there is a positive compensation between the attributes. They both yield degrees of membership of the resulting fuzzy set which are on or below the lowest degrees of membership of all intersecting fuzzy sets. Max-operation "or," on the contrary, amounts to a full compensation of lower degrees of membership by the maximum degree of membership. Despite their algebraic weaknesses, sum and product functions have been suggested as more appropriate in their semantics than the max/min operations (Gaines 1977). Mamdani and Assilian (1975) report no significant variation in the overall control policy with the different forms of fuzzy connectives. Zimmermann and Zysno (1980) have argued that new additional operations that imply some degree of compensation will have to be defined. They have generalized the classical concept of connectives by introducing an empirical parameter γ which may be interpreted as a grade of compensation. They define

$$\mu_{A \oplus B} = \mu_{A \cap B}^{1-\gamma} \cdot \mu_{A \cup B}^{\gamma} \qquad (23)$$

and use the sum and product operations. Their argument is that man has a decision rule enabling him to choose the right connective for each situation.

It may well be, however, that in real world applications where there is essential redundancy and robustness in the problem formulation that the precise form of fuzzy function does not matter (Gaines 1977).

5.4 Approximate Reasoning as Decision Support

The concepts of the theory of fuzzy sets have been applied to real world problems (see for example Zadeh *et al.* 1975; Gupta *et al.* 1977; Gaines and Kohout 1977; Gupta *et al.* 1979; Mattila *et al.* 1980).

Approximate reasoning is an appropriate tool for modeling heuristic decision rules. In control theory approximate reasoning has been used successfully to design fuzzy automatic controllers (Mamdani 1977). These controllers have performed very well; they have turned out to be very suitable as prescriptive models when simple structured decisions are modeled.

When applied to modeling heuristic rules in unstructured decision making, approximate reasoning can be used to design descriptive simulation models (see Freeling 1980). In the area of individual decision making, the analysis of human problem solving is well known for being based on computer simulations (Newell and Simon 1972).

Descriptive simulation models offer a clear, easy, fast and cheap method for investigating complex decision situations (Kickert 1978; Anderton and Denmead 1976). Some descriptive models based on approximate reasoning have been reported (see for example Kickert 1979; Dubois and Prade 1980). The structure of the linguistic simulation model is presented in Figure 4 (Kickert 1978).

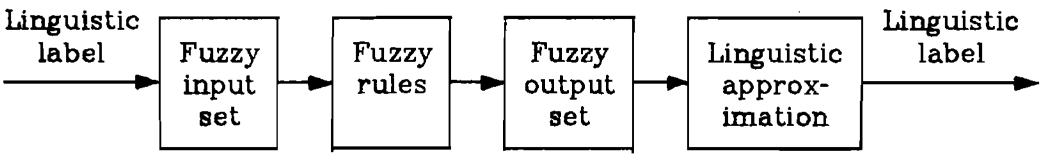


Figure 4. The structure of the linguistic simulation model. (Source: Kickert 1978)

Computer programming languages have also been developed for linguistic modeling (see for example Wenstøp 1976; 1981).

In multiple objective decision making, approximate reasoning provides an excellent tool for investigating the properties of the attribute set in cases where the independence conditions do not hold. The decision maker is asked to describe his preference structure for the present decision situation by using the assessed attribute set. This description is called the script of the decision problem. The script is converted into a set of statements using linguistic variables, connectives, negations, hedges, fuzzy implication, and compositional rule of inference. These statements are further converted into their respective mathematical formulations. When these formulations are combined in an appropriate way, a descriptive simulation model of the decision process is generated. This model includes the decision maker's preference structure. The model is a rough preliminary approximation of the real decision process; it must be adjusted using sensitivity analysis and statistical analysis. In complex decision making, descriptive simulation should be adopted before anything prescriptive can be said.

Fuzzy theories for decision making seem rather to have originated from the wish to apply fuzzy theory than to have been invented or developed in order to solve practical problems (Kickert 1978). To determine the real applicability of the theory, further research on fuzzy decision models will have to originate from real world problems.

6. DECISION SUPPORT FOR TECHNOLOGY DEVELOPMENT EVALUATION

Decision support system design can be divided into the following four phases:

1. Define the required characteristics of the system.
2. Structure the objectives.
3. Investigate the properties of the attribute set.
4. Structure the system.

A decision support system for technology development evaluation is presented in the following sections.

6.1 The Required Characteristics of the System

In Chapters 1, 2, and 3 the required characteristics of a decision support system for technology development evaluation were developed. The characteristics are:

1. The system needs clear and unique objectives that operationalize the purpose of the organization or activity.
2. Because a single objective or attribute is not sufficient to capture the whole utility of a technology development program, the system must be able to deal with multiple objectives.
3. In order to be able to prescribe, the system must at least to some extent describe the evaluation process.
4. The system is rather a means of learning and adoption than one of optimization, and thus it should be able to utilize the past experience of the organization.

5. The system must be simple, easy to use, and easy to understand.
6. The system should support the decision maker in overcoming his most obvious weaknesses: poor statistical ability and inconsistent logic.
7. The system must be compatible with the organizational procedures. It should be an integral part of the technology planning process.
8. Because subjective judgment plays a substantial role in technology development evaluation, any system incapable of incorporating this judgment is inadequate. The system must be able to deal with subjective and qualitative data.
9. As the system can only capture a part of the evaluation process, the system must be compatible with processes outside its scope.
10. No standard systems are available. Each system must be tailored to the organization.

6.2 Structuring the Objectives

Structuring the objectives is the basis for the systems design. Generating the objectives is an unstructured strategic planning decision for which general problem solving techniques (see Section 2.5) have to be employed. In technology development evaluation, the importance of past experience has been emphasized strongly. Consequently the problem solving strategy for generating prior evaluation objectives could well be the use of analogy where the analogous decision would be the posterior evaluation of technology development programs. Instead of trying to assess the objectives for prior evaluation directly, one may rather look at the completed programs and try to characterize successful programs in comparison to failures.

There are many arguments that support the idea of using posterior evaluation as an analogous problem to generate the prior evaluation objectives:

1. posterior evaluation is much easier than prior evaluation because the data is more accurate and the uncertainties are smaller,
2. posterior evaluation is a better known problem than prior evaluation. Many studies of posterior technology development evaluation have been reported (see for example STU 1978; CEC 1979a; b; Irvine *et al.* 1981; NTNF 1981),
3. posterior evaluation is as an analogous problem very close to prior evaluation,
4. some scholars have proposed the use of posterior evaluation as a check of the prior evaluation (Blake 1978; Harman 1980).

When a proper set of objectives has been generated the objectives have to be transformed into prior evaluation objectives. Some of the objectives may remain the same, especially those connected with the economy and the impacts of the programs. Some of them, however, have to be redefined. In particular, the objectives that describe the quality of the realization of the program have to be converted to objectives prescribing the prospectives for successful realization of the proposed program.

This conversion requires careful consideration and experience. However, there is a well established tradition used by innovation research to compare projects that have led to successful innovations with those that have led to failures in particular companies (see for example Freeman 1974; Rothwell 1974; 1977; Rubenstein *et al.* 1976). The same principle can be used to facilitate the conversion of the posterior evaluation objectives to prior evaluation objectives in technology development. This, however, requires that the data on the possible factors influencing success (basic information) are collected together with the posterior evaluation. When the posterior evaluation results and the factors are combined in an adequate way, a prior evaluation objective set can be generated.

To facilitate structuring, the objectives should be arranged in a hierarchy (see Section 4.3). Finally, the compatibility of the new evaluation objectives with the purpose of the organization has to be checked. The process of generating the prior evaluation objectives is presented in Figure 5.

6.3 The Properties of the Attribute Set

The attributes for the objectives must be generated (see Section 4.3). The attributes may use objective, subjective, or qualitative scales. The use of different scales will be discussed in Section 7.

It is important to analyze the properties of the generated attribute set to understand how the objectives should be used in the evaluation. It may be more important to analyze the attribute set than to assess the

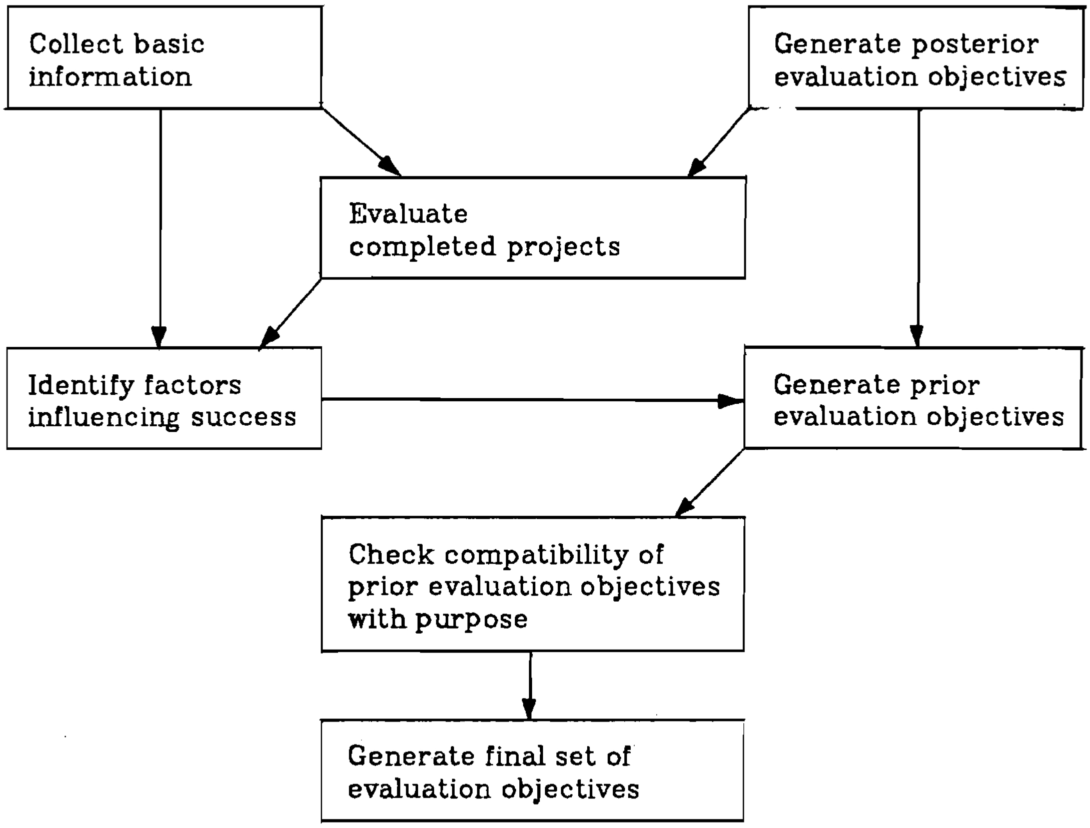


Figure 5. The process of generating the prior evaluation objectives.

final total preferences for the alternatives. The analysis raises questions about the right interpretation of the objectives and enchances discussion on the use of the objectives.

The methodologies that can be used in the analysis are those presented in the preceding chapters: the multiple attribute utility theory and the fuzzy decision theory.

The choice between the two methodologies depends on the form of the consequence values and the independence properties of the attribute set. If the consequence values are deterministic and the subsets of the attribute set are preferentially independent, the form of the total preference function is additive (7). If the consequences are defined as probability distributions and the attributes are additive independent, the form of the total preference function is additive (8). If every subset of the attribute set is utility independent the total preference function is multiplicative (9) and if every attribute is utility independent the function will be multilinear (10). If the consequence values are not deterministic or probabilistic or if none of the independence conditions hold, the concepts of the theory of fuzzy decision making must be used to simulate the decision process. Where the consequence values are uncertain, they can be approximated by using linguistic variables. If the independence conditions hold, the procedure of generating the fuzzy set induced by a mapping (20) provides a proper tool for the analysis. If, however, the form of the total preference function is unknown, one has to use either some predetermined fuzzy decision model (18), (19) or the principles of approximate reasoning for the simulation. In Table 2 the form of the aggregation model for different forms of consequence values and independence properties of the attribute set is presented.

Analyzing the properties of the attribute set may, of course, influence the set and result in its reformulation. As with the generation of the objectives, analyzing the properties of the posterior evaluation attribute set before the analysis of the prior evaluation attribute set may be useful.

Table 2. The forms of the consequence values, independence conditions and aggregation models.

Consequence values	Independence conditions	Aggregation model
Deterministic	attr. set PI	$\sum_{i=1}^{n} k_i v_i(x_i)$
Stocastic	attributes AI	$\sum_{i=1}^{n} k_i U_i(x_i)$
	attr. set UI	$\prod_{i=1}^{n} [K k_i u_i(x_i) + 1]$
	attributes UI	$k_1 u_1(x_1) + k_2 u_2(x_2) +$ $k_{12} k_1 k_2 u_1(x_1) u_2(x_2) \quad (n=2)$
Linguistic	hold	$\sup_{x_1, \dots, x_n : G(x_1, \dots, x_n)} \bigwedge_{i=1}^{n} \mu_{B_i}(x_i)$
	do not hold	$(\bigcap_{i=1}^{n} G_i) \cap (\bigcap_{k=1}^{K} C_k)$
		$\bigcap_{i=1}^{n} (\bar{B}_i \cup G_i)$
		approximate linguistic model (script, statements, mathematical formulation

6.4 The Evaluation System

A technology development evaluation support system should be composed of three subsystems: the prior evaluation system, the aggregation support system, and the performance evaluation system, which together provide the required characteristics of the system.

The three subsystems and their relations to each other and to the program management phases are presented in Figure 6.

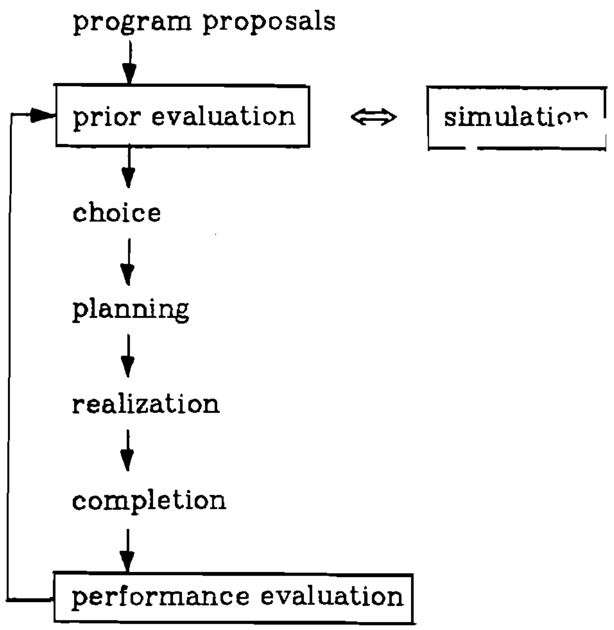


Figure 6. The three subsystems of the technology development evaluation system and their relations to each other and to program management phases.

The required system properties (see Section 6.1) and the characteristics of the proposed system are presented in Table 3.

The prior evaluation system collects the ideas and proposals for new technology development programs in some systematic way. It defines the organizational procedures and responsibilities in the evaluation process. It defines the form and content of the information required for the evaluation as well as the evaluation objectives, principles, and attributes that should be used in the evaluation.

When the attribute values for the proposals have been assessed the methodologies used to analyze the properties of the attribute set can be used to simulate the aggregation of the attributes. The simulation model describes the aggregation and provides a means of checking the

Table 3. The required properties and characteristics of the proposed system.

The system must:	The characteristics of the proposed system
have clear objectives	Objectives are generated by means of posterior analysis and are used explicitly by the system
be able to deal with multiple objectives	All the subsystems use multiple objectives
be descriptive	The simulation model is mainly a descriptive model
be a means of learning and adaptation	The performance evaluation system establishes a learning process
be simple	The system is composed of three simple subsystems
support statistical analysis	The performance evaluation system produces statistical summaries
support the logic of reasoning	The simulation model supports the logical process
be able to use subjective data	All subsystems use explicitly subjective and qualitative data
be compatible with the whole evaluation process	The system is an integrated part of the project management process
be custom-designed for each organization	The system is designed by using the posterior evaluation study

consistency of the logical process used in intuitive aggregation. The simulation model is not aimed at prescribing a unique preference order for the proposals but at providing a support system that interacts with the evaluator.

If the form of the total aggregation turns out to be additive, the aggregation does not have to be supported very strongly, because the natural form of intuitive aggregation is additive (see Section 4.8). If the form is multiplicative or multilinear or if the total preferences are assessed by using approximate reasoning, somewhat stronger support is needed. If the procedure for assessing a fuzzy set induced by a mapping must be used, the aggregation has to rely strongly on the prescription produced by the simulation model.

The evaluation of technology development proposals should be supported by a performance evaluation system (see Section 3.4). The system defines the organizational procedures and responsibilities of the performance evaluation. It defines the performance evaluation attributes and the form of information to be collected. The performance evaluation system provides a feedback from the performance to prior evaluation. By summarizing the performance evaluation results, the system establishes a learning process within the organization. The system measures how well a completed program was to perform in relation to its planned goals and provides a tool for quality control. The performance evaluation system also helps to reveal possible changes in the evaluation objectives.

7. EVALUATION SUPPORT AT THE TECHNICAL RESEARCH CENTRE OF FINLAND

7.1 Technical Research Centre of Finland (VTT)

The Technical Research Centre of Finland (VTT) is a non-profit technology development institution that carries out research and development in a wide range of fields of technology at its thirty laboratories. The purpose of the Research Centre is to maintain and raise the level of technology in Finland and to meet the research and testing needs of the public and private sectors by using, creating, and acquiring technological and economic knowledge.

VTT's activities are financed by the state budget (about 40%) and external income (about 60%) from research contracts with industry and public authorities. VTT has more than 2,200 employees and a total budget of about US$ 50 million. The state budget financing is used mainly for financing technology development programs and projects. The contract research is more often connected to development.

The thirty laboratories are organized into three research divisions: the Division of Building Technology and Community Development, the Division of Materials and Processing Technology, and the Division of Electrical and Nuclear Technology. Each division is directed by a research director who together with the general director and administrative director form the board, which is the highest decision making body at VTT. VTT's organizational structure is presented in Appendix 1.

VTT's laboratories are relatively independent. Each is responsible for their own performance and results as defined by three concepts: the relevance, quality, and economic result of the performance of the laboratory.

The relevance requirement means that the research carried out by the laboratory must concentrate on important and relevant problems of the economy and society and that the research effort outside VTT must be properly taken into account. The quality requirement demands that all research and development work must be of high quality, irrespective of the purpose of the work. Responsibility for economic result means that each laboratory must be able to cover all its own expenditures. This applies also to individual programs and projects.

7.2 Evaluation of the Program and Project Proposals

Program and project evaluation is a process usually made up of three successive phases. Individual scientists and research engineers very often have a decisive role in the evaluation process as they are the main source of new research ideas, and often make the decision as to whether or not to formulate the idea into a proposal. Also, if an idea is presented from outside VTT, it is the individual scientist who decides whether the process leading to a possible research contract will be set into motion.

The laboratory director must approve all programs and projects to be carried out in his laboratory. He approves research contracts and decides on the use of the budget allocations to the laboratory. He also approves all bids and applications for financing to be sent out from the laboratory. The number of proposals the laboratory director must evaluate can reach 200 or more annually.

VTT's board has funds reserved for its disposal, which it allocates directly to technology development programs and projects. Applications for financing from some of the most important public financiers (for example the Ministry of Trade and Industry) are ranked by the board before being sent further. Bids for financing from the board or those that are ranked by the board are evaluated by the division directors. The number of these proposals is about 200 per division annually. The programs and projects supported by these funds represent roughly one third of the total research and development effort of VTT.

VTT's technology development programs consist of number of projects with common goals. The average size of a program has been about 35 man-years and their duration three years. The programs are usually jointly financed by the board, participating laboratories, the Ministry of Trade and Industry, and industry. The aim of most of the programs is to develop new technologies that are expected to have great importance to the Finnish economy. Among the technologies that have been developed are biotechnology, digital image processing, automation in manufacturing, and telecommunications.

The process used by VTT to evaluate program and project proposals is presented in Figure 7.

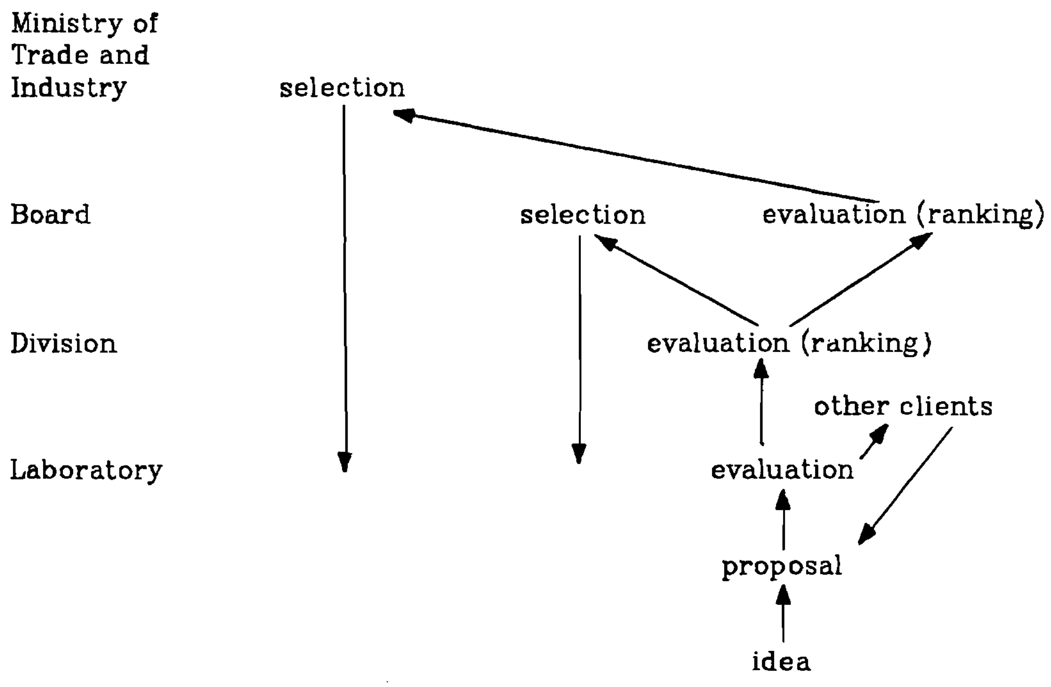


Figure 7. A schematic presentation of the evaluation process a VTT.

7.3 Posterior Evaluation Study

In 1981 the board at VTT decided to carry out a study on the posterior evaluation of the research performance of four of VTT's laboratories.

The goals of the project were:

1) to study possibilities for evaluating research performance in technology development institutions in general

2) to generate evaluations of the performance of four of VTT's laboratories (Computing Office (ATK), Laboratory of Structural Engineering (RAT), Metals Laboratory (MET), and Electrical Engineering Laboratory (ELE))

3) to collect the necessary background data for evaluation system design

4) to acquire experience and information that could be used to support the prior evaluation and selection of research programs and projects at VTT.

Because a substantial part of the research is confidential, any evaluation based on published material alone would be inadequate. Consequently the evaluations were performed by evaluating a restricted number of completed projects (about 30 projects per laboratory). The projects were evaluated by the contractor or the financier of each project, who was personally interviewed. A questionnaire was designed for the interviews. A set of evaluation attributes was generated after some test interviews. The questionnaire was designed to give evaluations on the attributes that further reflect the relevance, quality, and economic result of the projects. The three concepts of responsibility for results together with the evaluation attributes establish an objective hierarchy, which is presented in Figure 8. The test interviews revealed that the attributes reflecting relevance of the project were not appropriate for all VTT's projects. Consequently differing sets of relevance attributes were designed; one for commissioned projects (type A), and the other for publicly financed general projects (type B). The attribute set for the projects of type A is:

$$X_A = \{R_1, R_2, R_3, Q_1, Q_2, Q_3, Q_4, Q_5, Q_6, E_1, E_2\} \tag{24}$$

and for the projects of type B:

$$X_B = \{R_3, R_4, R_5, Q_1, Q_2, Q_3, Q_4, Q_5, Q_6, E_1, E_2\} \tag{25}$$

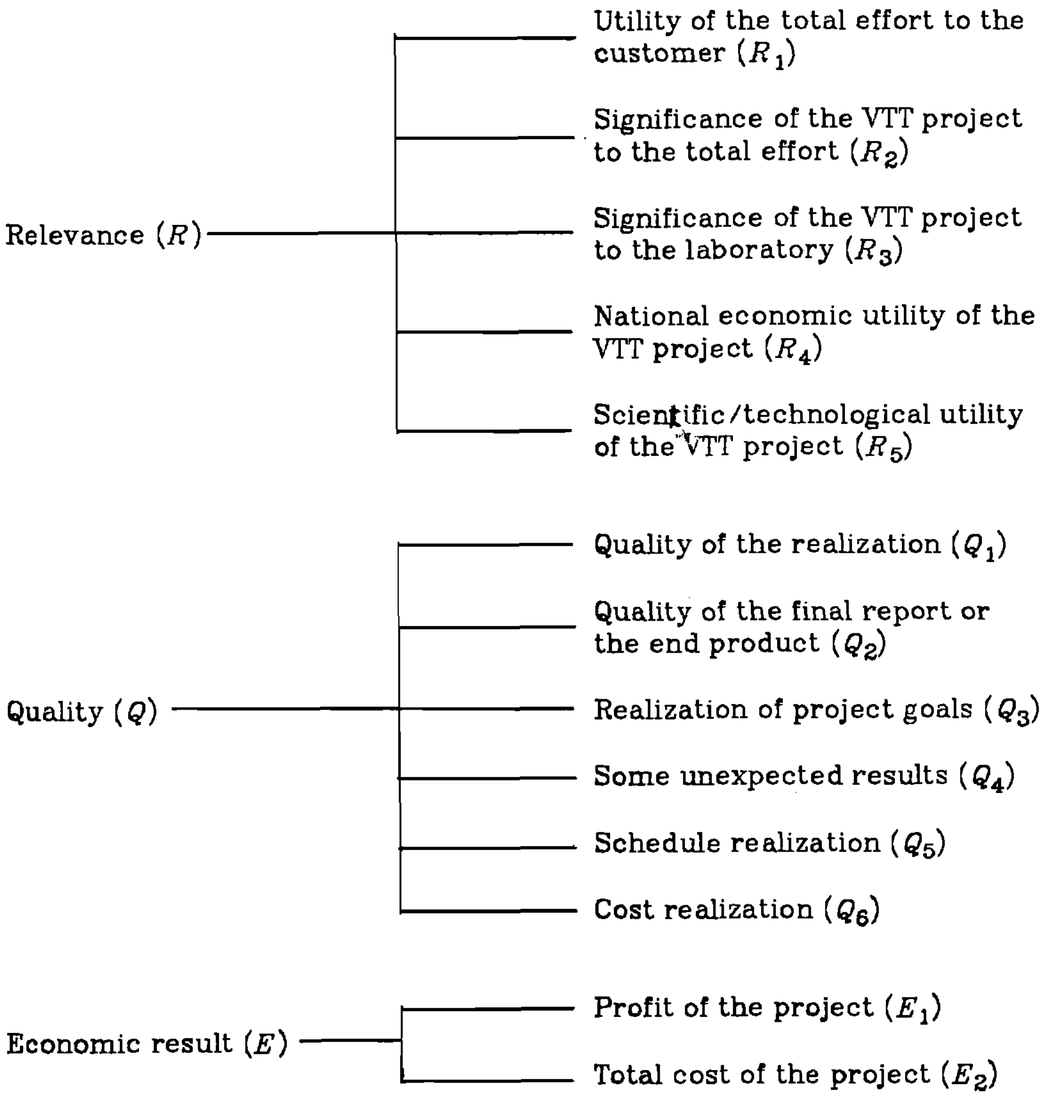


Figure 8. Posterior evaluation attributes for VTT projects.

Most of the attribute values were collected in the interviews (R_1,R_2,R_4,R_5,Q_1,Q_2,Q_3,Q_4) but some had to be collected from the VTT's own data files (Q_5,Q_6,E_1,E_2) and R_3 was assessed by interviewing the laboratory directors. The summary of the questionnaire is presented in Appendix 2.

Some background information about the projects was collected from inside VTT and added to the assessment of some of the attribute values. This information was called basic information about the projects. The basic information variables are presen:. .: in Appendix 3.

The reliability of the questionnaire was checked by interviewing about thirty pairs of persons so that the persons in each pair had the same kind of relation to the project. In this way a sample of thirty cases was obtained.

The developed questionnaire is a kind of measure of the impacts of research and development. It provides an alternate approach to economists' attempts to measure the impact in monetary terms (see for example Mansfield et al. 1977). The questionnaire included objective and subjective quantitative scales, categories and open answers.

7.4 The Properties of the Attribute Set

Instead of generating the prior evaluation attributes directly, the properties of the posterior evaluation attribute set was analyzed. The set of higher level objectives $\{R,Q,E\}$ common to both attribute sets was analyzed first.

To assess preferential independence, it is sufficient to check whether every pair of attributes is preferentially independent of its complement. The pair $\{R,Q\}$ is PI of Q but neither $\{R,Q\}$ nor $\{Q,E\}$ is PI of their respective complements. This is due to the evaluation principle at VTT which states that if the project is paid for completely by the customer, VTT will not be responsible for the relevance of the project. The commission will be accepted if VTT has the required resources and the work belongs to VTT's field of activity. The set $\{R,Q,E\}$ is not preferentially independent and consequently an additive total value function cannot be used.

A concept "successful project" can be defined as a fuzzy set (A). Its membership function can be assessed by using the three higher level objectives with the attribute set $\{R,Q,E\}$. Attributes are measured on subjective quantitative scales. A statement representing the above-mentioned evaluation principle would be: a successful project is qualitatively well performed and either relevant or economically good. Linguistic variables, qualitatively well performed, relevant, economically good, are defined as fuzzy sets (B_R, B_Q, B_E) with respective membership functions $\mu_B(r)$, $\mu_B(q)$, $\mu_B(e)$. The statement a successful project = B_Q and $(B_R$ or $B_E)$ gets the form:

$$\mu_A(r,q,e) = \min(\mu_B(q), \max(\mu_B(r), \mu_B(e)) \quad (26)$$

if max-min functions are used to represent the connectives "and" and "or." The formula would be of the form:

$$\mu_A(r,q,e) = \mu_B(q)(\mu_B(r) + \mu_B(e) - \mu_B(r)\mu_B(e)) \quad (27)$$

if the algebraic product and sum of the membership functions were used to represent the connectives.

As there is only one output set A the membership value $\mu_A(\cdot)$ is a direct measure of the preference for the project.

One problem in using higher level objectives for evaluation is that the three attributes are not sufficiently comprehensive and measurable. Consequently, assessment of the consequence values and their membership values is extremely difficult.

The posterior evaluation attribute set provides a more measurable and comprehensive set for the evaluation. The attribute values are measured either on subjective quantitative scales (R_1, R_2, R_3, R_4, R_5, $Q_1, Q_2, Q_3, Q_4 : 1 \cdots 5$) or on objective quantitative scales (Q_5: ± months, Q: realized/planned, %, E_1: (external financing − costs)/costs, %, E_2: in thousand US$). The following assessment is made for B type projects.

A relevant project would be one whose significance to the laboratory (R_3) or national economic utility (R_4) or scientific/technological utility (R_6) is high. If high R_3, high R_4 and high R_5 are again defined as linguistic variables ($C_{R_3}, C_{R_4}, C_{R_5}$) with membership functions $\mu_C(r_3)$, $\mu_C(r_4)$, $\mu_C(r_5)$ the statement would be (min-max formulations):

$$\mu_B(\overline{r}) = \max(\mu_C(r_3), \mu_C(r_4), \mu_C(r_5)) \tag{28}$$

where $\overline{r} = (r_3, r_4, r_5)$.

A project is performed qualitatively well if the realization (Q_1) and the end product (Q_2) are of high quality and if the goals of the project have been achieved (Q_3) or if something useful has come up instead (Q_4) and if schedule delay (Q_5) and cost overruns (Q_6) are not too big. Again defining the used propositions as linguistic variables and fuzzy sets, a membership function for a qualitatively well performed project can be defined:

$$\mu_B(\overline{q}) = \min(\mu_C(q_1), \mu_C(q_2), \max(\mu_C(q_3), \mu_C(q_4)), \mu_C(q_5), \mu_C(q_6)) \tag{29}$$

where $\overline{q} = (q_1, q_2, q_3, q_4, q_5, q_6)$.

A project is economically good if it is profitable and it is of proper size.

$$\mu_B(\bar{e}) = \min(\mu_C(e_1), \mu_C(e_2)) \qquad (30)$$

where $\bar{e} = (e_1, e_2)$.

Because all the projects are of type B the relevance must always be considered and consequently the statement would be: a successful project must be qualitatively well performed and relevant and economically good. The total preference function would consequently be of the form:

$$\mu_A(\cdot) = (\min(\max(\mu_C(r_3), \mu_C(r_4), \mu_C(r_5)), \mu_C(q_1), \mu_C(q_2), \max(\mu_C(q_3), \mu_C(q_4)), \mu_C(q_5), \mu_C(q_6), \mu_C(e_1), \mu_C(e_2)) \qquad (31)$$

The respective formulation by using sum and product would be:

$$\mu_A(\cdot) = (\mu_C(r_3) + \mu_C(r_4) + \mu_C(r_5) - \mu_C(r_3)\mu_C(r_4) - \mu_C(r_4)\mu_C(r_5) - \mu_C(r_3)\mu_C(r_5) + \mu_C(r_3)\mu_C(r_4)\mu_C(r_5))\mu_C(q_1)\mu_C(q_2)(\mu_C(q_3) + \mu_C(q_4) - \mu_C(q_3)\mu_C(q_4))\mu_C(q_5)\mu_C(q_6)\mu_C(e_1)\mu_C(e_2) \qquad (32)$$

In Table 4, ten B type projects of the Computing Office are ranked by using (31) and (32). The membership functions for C_{R_3}, C_{R_4}, C_{R_5}, C_{Q_1}, C_{Q_2}, C_{Q_3}, C_{Q_4} were approximated by using linear functions ($\mu(x) = 1/4(x-1)$). For C_{Q_5} the membership function was a linearly decreasing function and for C_{Q_6} and C_{E_1}, a linearly increasing function. For C_{E_2} the function is concave and the membership value for each attribute value was subjectively assessed.

In determining the unique preference order, if the projects have the same score ($\mu_A(\cdot)$-value) when using (31), the second lowest value is decisive and so on. The decisive value is signed in the matrix. q_1, q_3, and q_5 seem to be the most critical attributes; the relevance and economic

Table 4. Ranking of ten B type projects of the Computing Office by the steering committee members and by using (31) and (32).

Project	1	2	3	4	5	6	7	8	9	10
r_4	2	2	2	1	3	1	4	1	3	2
$\mu_C(r_4)$	0.25	0.25	0.25	0	0.5	0	0.75	0	0.5	0.25
r_5	2	2	1	2	3	1	3	2	2	2
$\mu_C(r_5)$	0.25	0.25	0	0.25	0.5	0	0.5	0.25	0.25	0.25
r_3	3	3	3	4	3	5	5	4	4	5
$\mu_C(r_3)$	**0.5**	0.5	0.5	0.75	0.5	1	1	0.75	0.75	1
q_1	4	2	3	4	3	4	4	4	3	4
$\mu_C(q_1)$	0.75	**0.25**	0.5	0.75	0.5	0.75	**0.75**	0.75	**0.5**	0.75
q_2	4	2	3	4	4	3	4	4	4	4
$\mu_C(q_2)$	0.75	**0.25**	0.5	0.75	0.75	0.5	**0.75**	0.75	0.75	0.75
q_3	5	2	4	4	1	4	4	3	3	4
$\mu_C(q_3)$	1	**0.25**	0.75	0.75	0	0.75	**0.75**	0.5	**0.5**	0.75
q_4	1	1	1	1	1	1	1	1	1	1
$\mu_C(q_4)$	0	0	0	0	0	0	0	0	0	0
q_5	0	4	4	6	9	2	0	3	0	6
$\mu_C(q_5)$	1	0.6	0.6	**0.4**	**0.2**	0.8	1	0.4	1	**0.4**
q_6	100	100	130	100	100	100	110	100	100	100
$\mu_C(q_6)$	1	1	**0.4**	1	1	1	0.8	1	1	1
e_1	+2	+20	-20	0	-32	-40	+20	-66	+4	-5
$\mu_C(e_1)$	1	1	0.6	1	0.5	**0.4**	1	**0.2**	1	0.9
e_2	12	12	44	15	34	75	12	15	9	16
$\mu_C(e_2)$	0.8	0.8	1	0.8	1	1	0.8	0.8	0.6	0.8
$\mu_A(\cdot)$ (31)	0.5	0.25	0.4	0.4	0.2	0.4	0.75	0.2	0.5	0.4
ranking (31)	2	8	7	5	9	6	1	10	3	4
$\mu_A(\cdot)$ (32)	0.33	0.01	0.02	0.11	0.03	0.09	0.27	0.02	0.10	0.12
ranking (32)	1	10	8	4	7	6	2	9	5	3

result attributes are critical in only one case each. The correlation between the rankings (31), (32) seems to be high (0.89) indicating that both connective rules give similar results.

Formulation (31) can easily be modified to include different weights for the attributes, which can be described using qualitative statements and transformed into mathematical form by defining a new fuzzy set with a membership function $\mu^{\alpha}(\cdot)$, where α represents the importance of the attribute (Yager 1978).

Alternative statements for a good project or additional requirements can easily be added by formulating the mathematical formulations of the statements and connecting them to the original formula by using connectives. Also, some relations may turn out to be fuzzy — these have to be described by fuzzy implication or the compositional rule of inference.

The presented example of linguistic modeling clearly demonstrates the most important advantage of this kind of analysis: the simplicity of the modeling.

It is important to remember that the main purpose of the analysis is not to prescribe a unique preference order but to study the properties of the attribute set.

Consequently generating the statements and looking at the cause and effect relations in the ranking may be much more useful and important than the ranking itself.

7.5 The Evaluation System for VTT

This section describes only a rough framework of the system. A detailed systems design has to be done elsewhere. The project and program evaluation system for VTT is similar in its structure to the general evaluation system presented in Chapter 6. It consists of the three subsystems: the prior evaluation system, the simulation model, and the performance evaluation system.

The performance evaluation system should be an integral part of the project management system. It uses the attribute set of the posterior evaluation study. Q_3, however, is assessed by evaluating the realization of each of the project goals separately. Q_3 is subdivided into a set of attributes, each corresponding the realization of one goal. The project manager gathers the attribute values for (Q_5, Q_6, E_1, E_2) before the last steering committee meeting. The committee assesses the rest of the attribute values and may make some comments on the performance in general and on the attribute values (q_5, q_6, e_1, e_2) in particular.

The performance evaluation is a formal measure for relieving the project manager of his responsibility. The performance evaluation system produces summaries for evaluating the performance of some laboratory, program, etc.

The prior evaluation is based on the goals of the project and on the prior evaluation attribute values. The goals should be defined as clearly and precisely as possible. It is important to be able to evaluate afterwards whether the goal was achieved or not.

The relevance and economic result attributes may remain the same as in the posterior evaluation but the quality attributes have to be transformed to measure the probability of qualitatively good performance. The quality attribute set is generated by combining the posterior evaluation results and the basic information variables to identify the factors contributing to the success.

The relevance attribute values are defined in qualitative form by the proposer. Instead of being asked directly what is the value of some attributes, the proposer is asked to describe the impacts of the project. By the same token, the quality attributes are assessed by asking how it is planned to carry out the project. This is necessary because it is impossible to transmit evaluation information on subjective quantitative scales. The evaluator (the laboratory or division director) then transforms the qualitative descriptions into linguistic variables and defines the quantitative attribute values.

Finally, the evaluator assesses the preference order either directly — by using his own intuitive aggregation function — or by generating the statements and using the simulation model to support the aggregation.

The simulation model is composed of the mathematical formulations of the alternative statements — e.g., (31) and (32) — and the membership functions. Its inputs are the attribute values assessed by the evaluator. The model produces the preference order and some information about the ranking procedure, such as the critical attributes.

The performance evaluation provides a means of checking the success of the prior evaluations. The relevance evaluation and the economic result evaluation can be checked directly by comparing the prior and performance evaluation attribute values with one another. Quality evaluation can be improved by studying the interactions between the prior quality evaluations and performance quality evaluations.

It is, however, extremely important to note that in this evaluation system framework one has to compare attribute values on quantitative subjective scales evaluated by different people (the laboratory or division director and the steering committees). These evaluations are by no means fully comparable and the results must be interpreted with this in mind.

8. SUMMARY AND CONCLUSIONS

8.1 Summary

In many countries technology development programs have become one of the main policy measures for enhancing future economic growth. In this study this policy is taken for granted. No effort is made to compare this policy to some other possible policies. Nor is the question of whether public support should be directed toward basic research, technology development, or development considered. The purpose of the study is to investigate possibilities for supporting decision making concerning choices between alternative technology development programs.

To be able to design support for evaluation one has to be cognizant of the latest developments in decision theory. Technology development evaluation is an unstructured strategic planning problem which cannot be supported by standard methodologies. Some general problem solving strategy has to be employed.

In designing the system, it is also necessary to understand the technology development process and identify its characteristics. Although numerous R & D evaluation models have been developed, none of them has been generally accepted or used. The premises for evaluation system design are developed.

The approach developed for solving the problem of system design for technology development evaluation support is to disaggregate the problem into pieces. First the objectives of the organization or activity have to be defined. These objectives operationalize the purpose of the organization and provide a comprehensive frame for the systems design. A proper set of objectives is generated using posterior evaluation of the completed programs as an analogous decision to prior evaluation of the proposals. Yet intuition still plays an important role in the assessment of objectives. The posterior evaluation objectives can be transformed to prior evaluation objectives by investigating the organizational factors influencing the success or failure of a project.

Secondly, the properties of the objective set have to be investigated. One must be able to measure the objectives. The properties of the objective set determine what kind of aggregation can be used in assessing the preference order of the alternatives.

Multiple attribute utility theory provides a tool for studying the properties of the objective set. If the independence conditions of the theory hold, simple aggregation functions (additive, multiplicative, or multilinear) can be used if the consequence values on the objectives are deterministic or stocastic.

If the independence conditions do not hold one can study the properties of the objective set and approximate the aggregation by using the concepts of fuzzy set theory. The form of the aggregation function is assessed by defining statements describing the relations between the objectives. The statements are transformed in a mathematical form and the aggregation process can be simulated.

The design of the system starts with defining the required characteristics of the system. The system itself is composed of three separate subsystems interacting with each other. The prior evaluation system structures the prior evaluation process and defines the evaluation procedures, objectives and responsibilities The simulation model utilizes the assessed aggregation function to support the intuitive aggregation. The performance evaluation system measures the performance of the organization and provides a check for the prior evaluation and selection decisions. The performance evaluation establishes a learning process in which the organization utilizes its own experience to orientate in the future.

The developed system was applied to the evaluation of technology development programs and projects at the Technical Research Centre of Finland (VTT). The evaluation objectives were defined in an posterior evaluation study. A questionnaire to measure the impacts, relevance, and quality of technology development projects was developed. The evaluations were generated by interviewing VTT's clients and steering committee members of the projects. The properties of the objective set did not justify the use of any simple aggregation function and consequently the aggregation was approximated by using the theory of fuzzy sets. Finally the frames for an evaluation system at VTT were presented.

8.2 Conclusions and Discussion

The bulk of this study has been to apply methods and theories within decision theory and system theory to support an unstructured strategic planning decision making: technology development evaluation. The role of these methods in supporting these kinds of decisions is quite different from the purpose they have been developed for. The support is based on an endeavor to divide the problem into subproblems that may be easier to structure than the original problem. The support is provided by modifying the decision process into a more systematic form and modeling some phases of the process. Still the role of modeling is rather descriptive than prescriptive. The improvement in decision making is a result of learning and increased understanding of the problem and the evaluation process. There is no objective way to measure the improvement and the rationale behind this kind of development is the belief that better understanding will result in better decisions.

The idea of analyzing the properties of the objective set and to design the support system accordingly is new. The multiple attribute utility theory has been developed and usually used for prescription but as has been shown it can also be a method for description and learning. The procedure to assess the fuzzy objective set is also new. The previous solutions have been based on some predetermined aggregation strategy but the developed procedure approximates the real aggregation by using the methods of fuzzy reasoning.

The developed system with its three subsystems and feedback loop resembles systems developed in control theory. The perspective of this study actually has been to look at technology development as a process. The proposed system is aimed to control and manage this process. It is, however, important to remember that all scientific activity is highly creative and the control and management activities should always be supporting and inspiring rather than restrictive. When one proceeds from the basic research towards the development end other factors like economic or time pressures may become dominant and require a change in the management style towards more restrictive and controlling. But because of the creative nature of technology development human intuition will have a dominating role in the management process. Systems analytic models can capture only a fraction of the whole management process and they will remain rough supporting tools of the management.

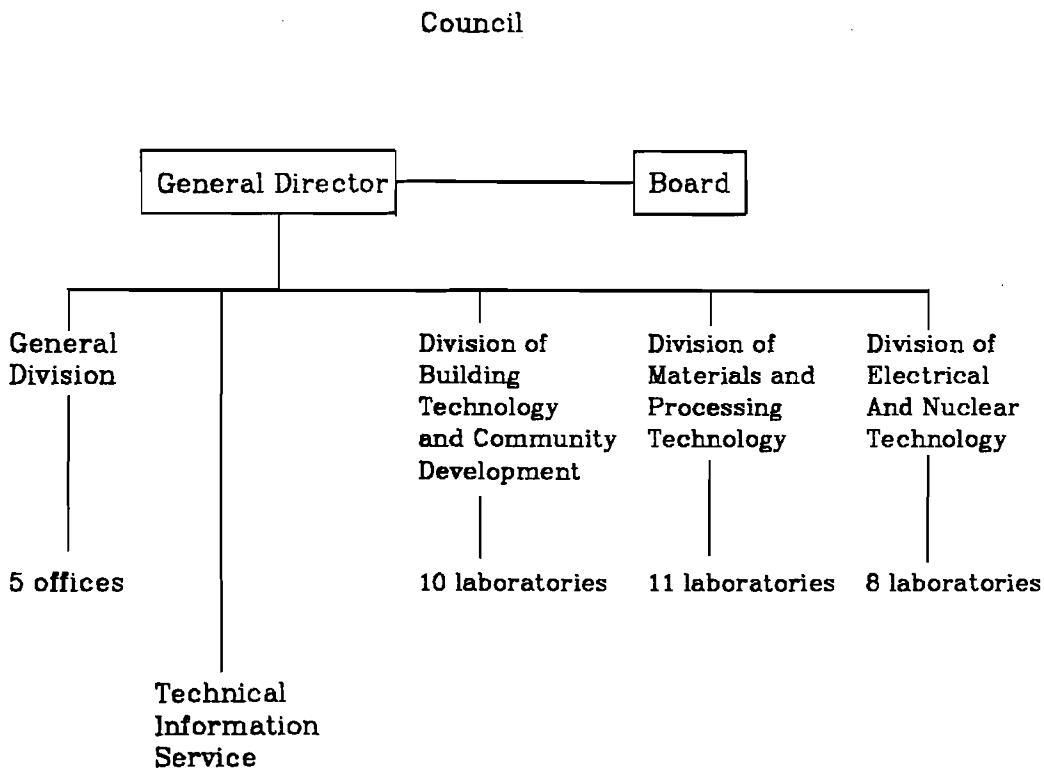
The study, especially the presented application, demonstrates that technology development evaluation can be supported by systems analytic methods. The used methodologies have turned out to be feasible but obviously they are not the only feasible tools for supporting technology development evaluation.

8.3 Some Guidelines for Future Research

Technology development process is still very poorly known. The process should be better understood. Some empirical, comparative research on different management measures and practices in technology development institutions would be very useful.

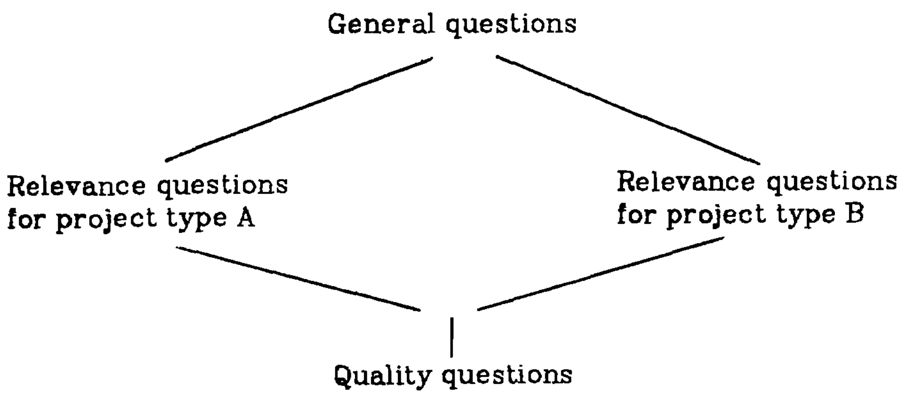
The methodologies to support unstructured strategic planning decision making are very rudimentary. Much more of the human decision making process has to be known before one may proceed in modeling from description to prescription. Theoretical development should be continued to develop more precise methodologies for validating other simple aggregation functions. The definitions of the fuzzy set theory for example those of connectives still lack the empirical verification. Also more has to be known about the actual meaning of linguistic statements so that they

APPENDIX 1: VTT'S ORGANIZATIONAL STRUCTURE



APPENDIX 2: INTERVIEW QUESTIONNAIRE (SUMMARY)

Structure:



Used scales:

A = quantitative objective scale
B = quantitative subjective scale
C = qualitative categories
D = open answer

could more precisely be modeled. A great practical problem in applying multiple attribute utility theory and fuzzy set theory is the assessment of the individual utility and membership functions. Easier and more comprehensible methods for assessing the individual functions have to be developed to improve the applicability of these theories.

The gap between theoretical development and practical applications is extremely large. Consequently more effort should be devoted to apply the developed methodologies to practical real live problems. This would also help to solve the problems in implementation.

The future development of decision support systems should concentrate on developing systems which have characteristics similar to those of the system supporting technology development evaluation developed in this study.

At VTT the detail design of the prior and performance evaluation system should be started. The objectives and the properties of the objective set should be discussed in the board and some simulation experiments should be done to investigate how good a description of the real evaluation process the simulation model can produce.

Interview Questionnaire:

General questions	scale
Interviewer	
Interviewed person	
• name	
• position	
• employer	
• relation to VTT project	

Relevance questions for project type A:

		scale
1.	What was the customer's total effort to which the VTT project was affiliated?	D
2.	What was the nature of the total effort?	C
3.	What were the goals of the total effort?	D
4.	What was the total size of the total effort?	A
5.	What is the present phase of the total effort?	C
6.	Has the total effort resulted in an innovation?	C
7.	How well are the goals of the total effort realized?	B
8.	Would you start the effort again if you had your present knowledge?	C
9.	What are the impacts of the total effort on the customer's:	
	• sales	B
	• market share	B
	• quality of the products	B
	• productivity	B
	• processing times	B
	• work safety	B
	• technical knowhow	B
	• national cooperation	B
	• international cooperation	B
	• other activities	B
10.	What is the total utility of the total effort to the customer?	B
11.	What are the indirect impacts of the total effort on the national economy?	
	• utilization of materials	B
	• energy demand	B
	• productivity	B
	• new innovations	B
	• balance of trade	B
	• employment	B
	• environment	B
	• work conditions	B

- adoption of new technology B
- research possibilities B

12. What is the total national economic utility of the total effort? B
13. What was the contract research given to VTT? D
14. To which phase of the total effort was the VTT project affiliated? C
15. What were the goals of the VTT project? D
16. Was the task of the VTT project difficult? B
17. How was the contact to VTT made? C
18. Why was the contract given to VTT? D
19. Was there any other way to solve the problem? D
20. What was the share of the VTT project of the total effort? A
21. What was the significance of the VTT project to the total effort? B

Relevance questions for project type B:

1. What was the purpose of the project? C
2. What was the type of the project? C
3. Where did the idea come from? C
4. What were the goals of the project? D
5. Was there any feasibility study performed? A
6. Was the task of the project
   - important B
   - common B
   - urgent B
   - difficult B
7. Why was the project performed at VTT? D
8. Was there any other way to solve the problem? D
9. Who are the users of the results? D
10. What are the impacts of the project on the national economy?
    - utilization of materials B
    - energy demand B
    - productivity B
    - new innovations B
    - balance of trade B
    - employment B
    - environment B
    - work conditions B
    - adoption of new technology B

	• research possibilities	B
11.	What is the total national utility of the project?	B
12.	What are the most important scientific and technical impacts of the project?	
	• scientific knowledge	B
	• knowhow in Finland	B
	• adoption of new technology in Finland	B
	• knowledge and ideas	B
	• new applications	B
	• new methods	B
	• technology import	B
	• national cooperation	B
	• international cooperation	B
13.	What is the scientific/technological utility?	B
14.	How did the project promote national cooperation?	D
15.	How did the project promote international cooperation?	D
16.	How are the results utilized?	D
17.	Has the project resulted in an innovation?	C
18.	Would you start the project again if you had your present knowledge?	C

Quality questions for both project types:

1.	Were there problems in organizing the project?	B
2.	Was the project plan good?	B
3.	Were the used research methods adequate?	B
4.	Was the used research equipment adequate?	B
5.	Was the performance of the project manager and team adequate?	B
6.	Was VTT's knowhow sufficient?	B
7.	Was the performance of the steering committee adequate?	B
8.	Were the conclusion right?	B
9.	Were there any problems in the cooperation?	B
10.	Was the project control adequate?	B
11.	Were the goals of the project realized?	B
12.	Was the realization of the project good?	B
13.	Was the final report good?	B
14.	Was the final product good?	B
15.	Are there any other comments concerning the quality?	D

16.	How are the results reported?	
17.	Was something unexpected developed?	B
18.	What was the realization of the time schedule?	A
19.	What was the realization of the cost plan?	A

APPENDIX 3: THE BASIC INFORMATON VARIABLES FOR EACH PROJECT

Total costs

Financing

- Budget financing
- Financing from the VTT board
- External financing from the public sector
- External financing from the private sector
- External financing from abroad
- Financing from other VTT laboratory

Profitability

Duration

Size

Cost Realization

Schedule Realization

Size of the Project Group

Number of Participating Laboratories

Number of Participating Outside Organizations

Steering Committee

- Number of representatives from the responsible laboratory
- Number of representatives from the other VTT laboratories
- Number of representatives from public financers
- Number of representatives from user organizations

Number of Meetings of the Steering Committee

Project Manager

- Status
- Degree
- Experience outside VTT
- Experience at VTT
- Number of publications
- Contribution to the project

Publications

- Written seminar or congress papers
- Written journal articles
- Written publications in VTT series
- Written publications in other series
- Planned seminar or congress papers
- Planned journal articles
- Planned publications in VTT series
- Planned publications in other series

Public — Confidential — Secret

Project Proposal Document

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