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AN ANALYTICAL PROCEDURE TO ASSIST DECISION-MAKING in a government research organization

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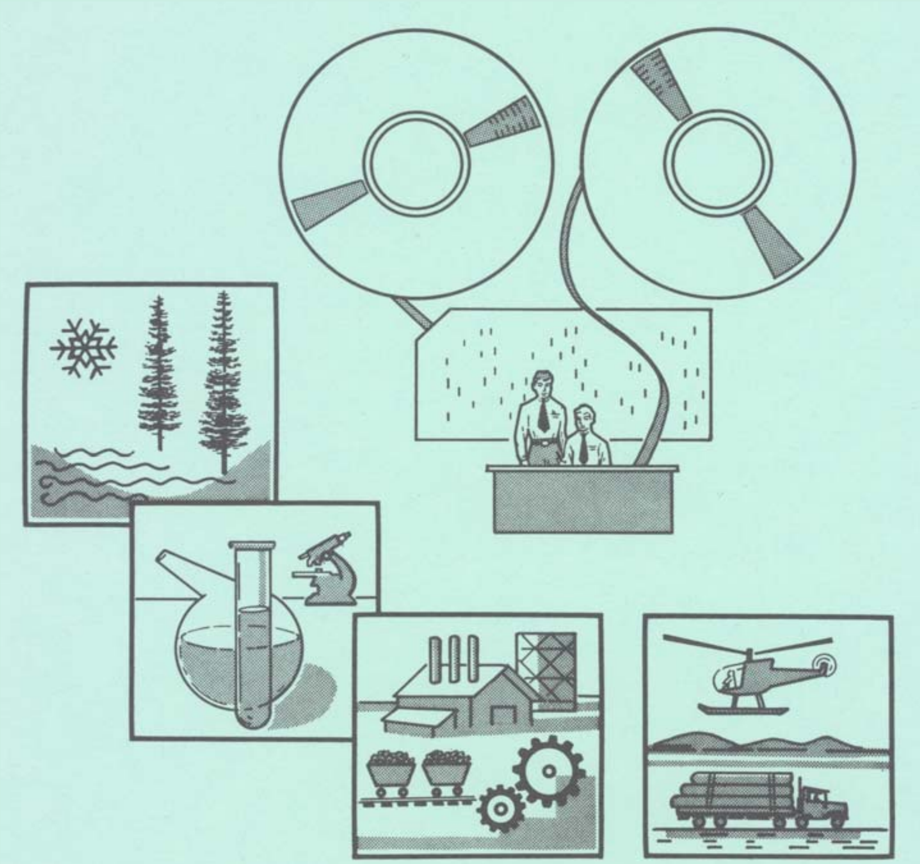

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FOREWORD

Evaluating proposals for inclusion in a research program is an important, continuing, and difficult decision process for the research administrator. He usually decides on the basis of intuition and knowledge. Typically, only a small amount of data and analysis is available to him before proposals are selected and molded into a research program.

Recognizing the potential for improving this process, the consistency and perhaps the quality of the decisions, the Forest Service started both theoretical and empirical studies in 1967. Theoretical work was done at the Pacific Southwest Forest and Range Experiment Station in cooperation with the University of California, Berkeley. The U.S. Forest Products Laboratory at Madison, Wisconsin, cooperated by providing data for both theoretical and practical work.

The procedures reported in this paper were developed by the Station in cooperation with the University of California, Berkeley. This report is a companion to *A Data Collection and Processing Procedure for Evaluating a Research Program*, published by the Station as USDA Forest Service Research Paper PSW-81.

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This paper considers the problem of planning research in two sections. First, a conceptual framework is proposed in which objectives, activities, and constraints of a government research organization are considered in a functional systematic manner. Second, a procedure is introduced that can assist decision-making in such an organization. Methodology, theoretical constructs, and empirical propositions from economics, operations research, and mathematical programing are used in developing the proposed procedure, and in substantiating its results.

In the conceptual framework of section one, research administration is viewed as a set of operations leading to the allocation of available resources among competing research activities. These operations consist primarily of acquiring, processing, and utilizing information. The two major categories of information involved are data on alternative research possibilities, and data on preferences among alternatives. Acquisition and processing of data in both categories are considered. Several major problems areas in public research planning, such as multiple objectives, uncertainty of research outcomes, and time preferences for future benefits are discussed within this framework.

The second section proposes a specific procedure to analyze alternatives and to assist a research planner in reaching allocation decisions. In this section, we also utilize the conceptual framework developed in section one to specify information requirements and to suggest methods of bringing the information together for analysis.

OBJECTIVES, ACTIVITIES, AND CONSTRAINTS

A government research organization can be usefully described in terms of objectives, activities, constraints, and the interrelationships between them. On the basis of Tinbergen's (1966) classification of policy variables, the objectives of a government organization can be defined as target variables. The research activities of the organization may be considered as instrument variables or strategies to be used in pursuing targets. Any remaining variables represent elements over which the administrator exercises a lesser degree of control. These uncontrolled variables should be considered fixed constraints. Understanding and identifying objectives, activities, and constraints are essential for planning operations. This section describes a framework to assist in identifying and understanding these variables for a government research organization.

Objectives and Effectiveness

Objectives for a government research organization are usually established through an interactive process of communication between various levels of the executive hierarchy. Broad statements of purpose are generally issued at the top. These provide guidelines for establishing more precise directives at lower levels. Eventually a detailed program of activities is generated by the research organization. Thus a process of identification, analysis, and specification takes place in which a list of targets or operational objectives is distilled from broadly spelled out recommendations. Whether or not this process of communication and interaction takes place in a highly structured manner, through institutionalized procedures and channels, or in a more informal fashion, the end result is a set of operational objectives which can be used as planning parameters. In operations planning, objectives are appropriately defined only when it is possible, at any point in time, to unambiguously determine the degree to which they have been accomplished. Measurable objectives have this property.

If an organization had a single objective, then alternative programs of activity could be ranked and evaluated in terms of their effectiveness in the achievement of this objective. Thus a standard of effectiveness would be readily available.

When an organization has several different objectives, such notion of effectiveness is generally not sufficient to establish a ranking of alternative policies. A performance matrix for three alternative plans in terms of three measurable objectives will illustrate this point:

	Objectives		
	1	*2*	*3*
Programs:			
A	1,000	20,000	500
B	500	20,000	1,000
C	500	20,000	500

Undoubtedly program C is least desirable, but it is not possible, on the basis of the information displayed, to decide between programs A and B. In fact, A performs better in terms of objective 1, and B performs better in terms of objective 3. This difficulty can be resolved only by introducing an equivalence ratio between objectives 1 and 3. The equivalence ratio of objective 3 in terms of objective 1 expresses the number of units of objective 3 which are equivalent to one unit of objective 1. In the example, program B is determined to be superior, inferior or indifferent to program A by the equivalence ratio of objective 3 in terms of objective 1. If the ratio is greater than one, program A is superior to program B.

The idea can be stated more generally. Given K objectives, K-1 equivalence ratios are needed to define a measure of effectiveness which can be used in ranking alternative action programs. Given a list of operational objectives for a government organization the specification of a corresponding list of equivalence weights represents a precise definition of the decision-maker's hierarchy of priorities.

On a higher level of generality the hierarchy of priorities among objectives can be considered as varying with the degree of achievement of the different objectives. For example, the desirability of objective 1 with respect to objective 2 may be assumed to vary according to the extent to which 1 and 2 are being achieved. This discussion of comparative desirability introduces the notion of a preference function familiar to readers of economic theory. The problem of measuring the effectiveness of multi-objective programs is a special case of the broader problem of aggregating noncommensurable items. An analytical solution of the problem entails the specification of a mapping that transforms multidimensional values into a one-dimensional measure. This mapping can be chosen to be an average or mean function. Thus an optimum average function would represent an ideal solution.

In multiple-objective planning, two sets of information items are necessary: a set of individual objective achievement measures, as arguments of the average; and a set of preference weights, as parameters of the average. In practice, it may be difficult to establish a sound data base for these items. Nevertheless, it is important to clearly define the types of information sought.

Information about measures of objective achievement can be characterized as "technical" or "factual." It consists in estimates of the expected effects of a specific plan of action as they contribute to individual objectives. As an example, consider the effects of a specified research activity on the gross national product, measured in dollars. This piece of information can be consolidated in the form of a numerical prediction representing a consensus among competent technical experts.

Information about preference weights can be viewed as pertaining to value judgments. It presupposes a specification of priorities among social objectives. Questions such as "What is the dollar value of one human life?", to choose a typical example, may have to be raised and answered in this context. Such information is to be established in the form of determinations and judgments reflecting some consensus. Only, here the experts are not so much the scientists or the technicians, but those empowered with the responsibility of interpreting the priorities of public interest.

The information outlined above may not possess the character of the "hard" data that one may find desirable for analysis. On the other hand, it is relevant data. Also, there is no *a priori* reason why the reliability of these data should not increase in proportion to the effort exercised in obtaining them. Securing a consensus through documentation and assembly of supportive materials should increase the reliability of data. The definition of effectiveness in terms of multiple objectives is determined by the type of information available. Examples of utilizing different types of information in formulating a multiple objective problem can be given for specified objective measurements, market-derived measures, and a mixture of the two.

Consider a government research organization with K objectives and P alternative plans of action, i.e., research programs. Assume that each objective is measurable in some specified units. Let O_{kp} represent the expected achievement of objective k using plan p. Let W_k be the priority weight of the kth objective on a specified ranking scale. This means, for instance, that one unit of objective 1 is worth W_1/W_2 units of objective 2. Assuming an arithmetic average function, an effectiveness measure for plan p can be expressed as

$$E_p = W_1 O_{1p} + W_2 O_{2p} + ... + W_K O_{Kp} \qquad (1)$$

This formulation can be displayed in "tableau" form *(fig. 1)*. Obviously it is not possible to calculate the efficiency of a plan according to formula (1) unless the Wk's are specified. This requirement corresponds to the common-sense notion that it is not possible to plan at all unless the hierarchy of priorities among objectives is known or agreed upon.

Alternative Plan	Measure of accomplishment in objective				Plan effectiveness
	1	2	. . .	K	
1	O_{11}	O_{21}	. . .	O_{K1}	$E_1 = \sum_k^K W_k O_{k1}$
2	O_{12}	O_{22}	. . .	O_{K2}	$E_2 = \sum_k^K W_k O_{k2}$
3	O_{13}	O_{23}	. . .	O_{K3}	$E_3 = \sum_k^K W_k O_{k3}$
.	.	.	. . .	.	.
.	.	.	. . .	.	.
.	.	.	. . .	.	.
P	O_{1P}	O_{2P}	. . .	O_{KP}	$E_P = \sum_k^K W_k O_{kP}$
Priority weights	W_1	W_2	. . .	W_K	

Figure 1–Multiple-objective effectiveness index as calculated on the basis of ideal measures of (a) achievement of objectives, (b) relative priority of objectives.

In other cases, economic information can be used to construct measures of effectiveness of public programs. These are cases in which attainment of social objectives can be readily translated into a notion of economic value. In many instances, government activities result in increased production of goods and services or in savings in the use of productive resources. When planning involves such activities, efficiency for a plan p can be defined as

$$E_p = Q_{1p} V_1 + Q_{2p} V_2 + \dots + Q_{Np} V_N \qquad (2)$$

in which Q_{ip} are measures of production increases or resource savings and V_i are the corresponding prices of commodities or resources. This formulation can be displayed in "tableau" form *(fig. 2).*

Formula (2) is analogous to formula (1), except that priority weights [W] have been replaced by market prices [V]. In other words, the prices generated by the market mechanism serve as reliable indexes of public preferences. On the other hand, there are situations in which public benefit may not be reflected in market prices nor even expressible in terms of economic values. In some cases, social objectives may not be equated with increased efficiency in production of marketable commodities. In other instances, public goals involve the production of services whose market pricing is either nonexisting or inadequate from a social viewpoint. Using economic incentives as criteria to decide upon the public desirability of certain government activities may also have the disadvantage of validating any inadequacies inherent in the social performance of the private sector. If these pitfalls are recognized, judicious use of economic data and economic justifications can provide assistance to government decision-making bodies–especially when a precise definition of political priorities is absent *(fig. 3).*

As a compromise solution a computation of efficiency based on formula (3) can be proposed:

$$E_p = W_p (Q_{1p} V_1 + Q_{2p} V_2 + \dots + Q_{Np} V_N) \qquad (3)$$

According to formula (3), the economic assessment of plan p–computed as in formula (2)–is adjusted by a factor, W_p, to account for possible divergences between economic and social performance of the plan. W_p is estimated on the basis of the proportion of net social benefits to net economic benefits expected from plan p. More precisely, let E_p be the over-all benefit of plan p. Assume that

$$E_p = E_p^* + EE_p$$

i.e., the total benefit can be broken down into an economic portion E_p^* and an extra-economic component EE_p. Then W_p is defined by the formula

$$Wp = Ep / E_p^* = 1 + EEp / E_p^*$$

In formulating plans, objectives can be specified as fixed targets or as open-ended performance dimen-

Alternative plan	Measure of product increased or resource saved in industry				Plan effectiveness
	1	2	. . .	N	
1	Q_{11}	Q_{21}	. . .	Q_{N1}	$E_1 = \sum_i^N Q_{i1} V_i$
2	Q_{12}	Q_{22}	. . .	Q_{N2}	$E_2 = \sum_i^N Q_{i2} V_i$
3	Q_{13}	Q_{23}	. . .	Q_{N3}	$E_3 = \sum_i^N Q_{i3} V_i$
.	.	.		.	.
.	.	.		.	.
.	.	.		.	.
P	Q_{1P}	Q_{2P}	. . .	Q_{NP}	$E_P = \sum_i^N Q_{iP} V_i$
Economic prices	V_1	V_2	. . .	V_N	

Figure 2–Multiple-objective effectiveness index as calculated on the basis of market derived measures.

Alternative plan	Product increased or resource saved in industry				EE factor[1]	Plan effectiveness
	1	2	. . .	N		
1	Q_{11}	Q_{21}	. . .	Q_{N1}	W_1	$E_1 = W_1 \sum_i^N Q_{i1} V_i$
2	Q_{12}	Q_{22}	. . .	Q_{N2}	W_2	$E_2 = W_2 \sum_i^N Q_{i2} V_i$
3	Q_{13}	Q_{23}	. . .	Q_{N3}	W_3	$E_3 = W_3 \sum_i^N Q_{i3} V_i$
.	.	.		.	.	. .
.	.	.		.	.	. .
.	.	.		.	.	. .
P	Q_{1P}	Q_{2P}	. . .	Q_{NP}	W_P	$E_P = W_P \sum_i^N Q_{iP} V_i$
Economic prices	V_1	V_2	. . .	V_N		

[1] "Extra-economic" adjustment factor.

Figure 3–Multiple-objective effectiveness as calculated on the basis of market derived measures as well as other parameters of social utility.

sions. For example, a goal of economic growth can be specified as "increase GNP by 5 percent." This increase represents a fixed target. The corresponding open-target specification would be "maximize GNP." Whether an objective is specified as a fixed or an open target makes a difference when competing plans are compared in terms of that objective. With respect to a fixed target, competing plans can be classified into two types: (a) those that achieve the specified target or better; and (b) those that fall short of the target.

All plans in either category are equivalent to all other plans in that category in terms of effectiveness, in other words, fixed target objectives can be stated as feasibility constraints.

Defining performance in terms of a plurality of objectives can be done in another way. One major objective can be specified as an open-ended effectiveness dimension. All other objectives can be stated as fixed effectiveness levels. This method reduces the problem of ranking alternatives under a multiplicity of objectives to the simpler case of a single objective. Alternative plans that satisfy minimum effectiveness requirements in terms of the fixed target objectives can be conveniently ranked according to the primary, open-ended objective.

Activities and Programs

A *program* can be defined as a list of activities to be carried out. In the planning stage a number of alternative programs can be considered. Effective planning consists of selecting the program having the best performance. In general it is advantageous to consider the largest possible number of alternative programs. Conceptually then, programs can be generated by specifying the complete set of activities which could conceivably be carried out, then defining alternative feasible programs as subsets of the complete set of activities. To be feasible a program must be consistent with constraints that limit the organization's freedom of action. For instance, a program may not be feasible because it requires an outlay in excess of the available budget. In other cases, a program may demand skilled services in excess of those which the organization can procure. In addition, organizational regulations and considerations reflecting requirements of internal cohesion may render some programs unacceptable.

An *activity* is usefully defined as an output-identified operational unit. This definition emphasizes the requirement that the output expected from a research activity determines its separate and distinct identity. Operational units so defined may or not correspond to administrative or budget accounting units. An administrative unit may embrace several "activities" or, conversely, one activity may involve more than one administrative unit. For planning purposes administrative units and planning units need not be identical.

Identifying the output of a research activity as a specific and clearly defined target is a necessary prerequisite for *a priori* evaluation and retrospective assessment of the activity itself. The expected output of a research activity may be collections of data, classifications of data, formulations of hypotheses, testing of hypotheses, or advancements of theories. In addition, research outputs might consist of applications of scientific knowledge which creates technological innovations in the form of new products or new processes. To assign a measure of socio-economic value to the expected output from a research activity, two sets of information are required: (a) the anticipated socio-economic effects of the expected research product; and (b) the time schedule in which these effects are expected to materialize.

In the process of identifying gains from research it may be convenient to separate economic and extra-economic gains. "Economic" gains are contributions to public good which can be readily assessed in terms of dollar measures. "Extra-economic" gains, or losses, represent that portion of foreseeable socio-economic effects which have not been adequately considered in the economic analysis of a research activity. Important aspects sometimes overlooked in the economic accounting of public value are: (a) macro-economic effects, such as repercussions on income distribution, rates of employment, etc.; and (b) externalities. Externalities occur whenever social gains or sacrifices are forced upon the public at large as byproducts of economic decisions on the part of private individuals or organizations. For instance, the social cost of air pollution does not appear as a production-cost component of auto manufacturers. Sometimes a government institution engages in a research activity which is simultaneously carried out by some other party. The public cost implicit in this duplication of effort as well as all other instances of "extra-economic" benefits or costs should be accounted for in the assessment of the socio-economic impacts of government funded research. This accounting can be done by (a) constructing a dollar measure of value of an activity on the basis of its predicted economic results; and (b) adjusting such measure by means of a "social priority multiplier" type of measure. The social priority multiplier should reflect the over-all social utility of a research activity relative to its strictly economic merits. Using this procedure a dollar measure of socio-economic value of a research activity can be obtained. Such a measure will be referred to as the activity's *benefit.*

A major difficulty encountered in the determination of "benefit" involves intertemporal value comparisons. Benefits from research accrue in time streams. How are benefits generated in earlier years to be compared with gains in later years? If benefits are expressed in dollar equivalent units, the problem can be stated in terms of discount rates, namely, what is a suitable rate of discount to compare dollar values produced at different points in time? This is a subcase of the more general problem of a multidimensional achievement function discussed in the subsection on objectives. In fact, dollar benefit in year t can be viewed as a different performance dimension with respect to dollar benefit in year t + 1. The choice of a discount rate in calculating the present value of a stream of future benefits is crucially important. Grossly speaking, a lower rate of interest [1] tends to make the present value of longer-term projects relatively larger compared to shorter-term projects; a higher rate would tend to make it relatively smaller. The issue of the rate of discount to be used in the analysis of government programs–the social rate of discount– is widely debated in the economic literature. Two conflicting sets of considerations affect the choice of an appropriate rate.

One set of considerations emphasizes the problem of optimum resource allocation between private and public sectors of the economy. No matter how the government finances its enterprises, whether through taxes, borrowing, or inflation, in real terms it takes away scarce input resources from the private sector. To allocate resources efficiently, public agencies should evaluate them by using the same rate of return as would be used in the private sector. This rate would include not only the average rate of return to funds invested by individuals in the business sector, but also that fraction of those earnings from investments that are taxed. If this line of reasoning were followed the government would, on the average, use higher. rates of interest than those presently used in computing present values of public projects (Baumol 1968).

The other set of considerations concerns the question of society's preferences. Individuals are more prone to forego present benefits in favor of future ones in public projects than in private projects. This may be so because they invest in a public enterprise knowing that others must also contribute through taxation. In other words, individuals will undertake more investment collectively than each person finds desirable to undertake privately because the extra sacrifice "becomes insignificant in comparison with the psychic gains and losses from others' investment" (Marglin 1963). This set of considerations may be used to rationalize the application of lower rates of interest in discounting dollar measures of future benefits in government projects.

These two polar positions reflect conflicting beliefs and attitudes concerning the comparative effectiveness of the machinery available in either the public or private sector for interpreting and implementing individuals' preferences concerning investments for future generations. In practice, a market-generated rate of interest can be relied upon as a guide in establishing discount rates suitable for government-financed programs. [2]

The length and shape of the time stream in which results will flow from a research activity depends in general on the level and intensity of the resource investment. Thus the benefit of a research activity, as measured by dollar present value, varies according to the magnitude of resources invested. Consequently, the dollar benefit measure attached to a research activity implies and presupposes a specific level of resource requirements.

Another major problem encountered in the quantitative specification of a research activity is the uncertainty surrounding the steps required for its successful completion and implementation. The process through which a research activity generates desired results can be viewed as a sequence of steps. Each step involves a particular obstacle to be breached. A breakthrough in each step is necessary for the research activity to produce its planned end results. If perfect knowledge existed about the steps required and the actions needed to overcome these obstacles, a research activity would not differ from an industrial production operation. [3] For typical research activities the necessary steps and associated operational requirements are not known *a priori.* As research progresses, new information becomes avail-

[1] The relationship between rate of interest i and rate of discount d is: $d = (1 + i)^{-1}$.

[2] See *Survey of use by Federal agencies of the discounting technique in evaluating future programs.* Report to the Joint Economic Committee of the Congress of the United States by the Comptroller General of the United States. Jan. 29, 1968.

[3] Technical uncertainty exists also in production activities, e.g., agricultural production, but to a lesser degree.

able concerning the steps required and the difficulties involved. It is then problematic, given a specified end result, to determine exactly the amount and timing of work and resource use needed to obtain it. Conversely, given a specified amount of resources available for a research enterprise it is difficult to determine exactly when a certain research target will be achieved.

The exact relationship between level and timing of resource use and level and timing of research output remains uncertain. As a consequence any explicit specification of benefit and resource requirements for a research activity is subject to a degree of uncertainty. Such uncertainty can be quantitatively expressed in a "chances of success" measure. This parameter introduces a probabilistic element in the quantitative assessment of a research enterprise. It expresses the degree of confidence that a specified time stream of resource use will yield a planned research result. The "chances of success" measure can be interpreted as a certainty equivalence factor for the benefit of a research activity. This factor converts uncertain benefits into the corresponding uncertainty-free values. Resource intensity, time of completion, and chances of success are three closely interrelated elements. Consequently several "versions" of a research activity can be conceived of, each one characterized by a particular triplet of values for the three parameters. In some cases it may be convenient to express the interdependence between resource intensity, time of completion and chances of success by means of a functional relation.

Constraints

A research program is feasible if it is consistent with the constraints affecting the organization. The various types of constraints include limited resources, minimum performance, internal allocation, and interdependence constraints.

Limited Resource Constraints

A government research organization is not endowed with unlimited amounts of resources with which to carry out its activities. The limitations on the availability of resources may affect (a) the money budgets available in each year of the planning period; (b) the availability of physical facilities, such as buildings, laboratories, or special equipment items; and (c) the availability of specially skilled personnel. To pass the feasibility test with respect to these constraints a research program must not require resources in excess of the amounts available in each category.

Minimum Performance Constraints

The benefit measure represents an over-all effectiveness measure based on all of the organization's objectives, but it may be desirable for the organization to specify separately minimum levels of achievement for certain specific objectives. Such minimum levels may be specified in terms of input units as well as expected output units. One such specific objective may be, for example, basic research [4] or pollution control research.

Internal Allocation Constraints

Some government research organizations, especially larger ones, may have an administrative structure involving several subunits with considerable degree of autonomy. A research program for the whole organization implies a certain allocation of the budget monies and other resources among the administrative subdivisions. If such allocations were to excessively penalize one or more of the subunits, the internal stresses generated could threaten the cohesion of the organization. A research program with these allocational implications may be ruled out as unfeasible. Constraints of this type could be stated as minimum budget requirements for each subdivision either as absolute amounts or as fractional shares of the total budget.

Interdependence Constraints

A research activity may be defined in such a way that it cannot be carried out unless one or more complementary activities are executed as well. This is an example of positive dependence. On the other hand, two or more activities may be mutually exclusive, i.e., only one out of a specified set of activities may be considered. This is a case of negative dependence. A typical case of negative dependence occurs when several "versions" of a research activity are proposed, each version characterized by a different level of resource use. If only one among these versions is allowed to enter the organization's research program a negative dependence constraint is present. Such constraint requires that the various "versions" of the same activity be mutually exclusive.

[4] In terms of the discussion on uncertainty in the section on Activities and Programs "basic research" can be characterized as highly uncertain research, i.e., research in which there are many unknown steps between inception and achievement of foreseen end results.

Interrelationships in Optimization Models

Objectives, activities, and constraints constitute the building blocks of optimization models. An optimization model may provide the basic framework for efficient organization planning. It can facilitate thorough understanding and rational utilization of information pertaining to a decision problem. A suitable optimization model serves to: (a) simulate the situation at hand; (b) postulate the conditions of rational behavior in the decision process analyzed; and (c) efficiently communicate the relevant data and knowledge of the problem. Simulation consists of selecting certain elements and relationships as representative of the situation under consideration, then formulating hypotheses regarding the nature of these relationships. Postulating conditions of rational behavior is equivalent to defining rules and criteria that identify the best or optimum decision. Efficient communication amounts to defining and using terms with a precise and constant meaning.

The mathematical formulation of a decision scheme consists of using mathematical symbols and conventions to specify the variables representing objectives, activities, and constraints, and the relations among these variables. Such formulations of decision problems have the advantage of allowing the conciseness and internal consistency inherent in the logical method to be exploited. They also afford the possibility of using mathematical optimization techniques and corresponding computational algorithms to determine best decisions.

In most concrete situations the variables relevant to the decision problem at hand are numerous and their interrelationships highly complex. A consequence of such complexity is the latitude left to the analyst in designing an appropriate scheme. In building a model, he invariably selects a particular set of facts as important and excludes others as immaterial. In an overly simple model, relevant variables and relations may be either omitted or too grossly approximated. Such a model would be of limited usefulness in the analysis of complex decision problems. As additional relevant variables are introduced and relations specified in greater detail, a model becomes more effective in providing meaningful answers. From a technical viewpoint, a variety of alternative procedures can be envisaged. Nonlinear as well as linear relations may be postulated, stochastic as well as nonstochastic variables may be specified, and dynamic instead of static assumptions may be introduced.

On the other hand, increasing the degree of complexity of a model involves some disadvantages. Not only does it become more difficult to find or develop appropriate mathematical techniques and computational algorithms, but, also, the information requirements for numerical implementation become more drastic. In some cases information may not be available in the amount and detail specified by the model; in others, the procurement of the information required may involve an expenditure in excess of the value of the answers that the model could provide. Thus a correct perception of the advantages and disadvantages associated with various degrees of complexity should assist the researcher in the selection of the model which is best suited for the analysis of a specific decision problem.

A decision model of research management, therefore, involves these phases: (a) definition of effectiveness criteria, (b) comparison of feasible research programs, and (c) selection of best research program. Examples of mathematical formulations of research planning aspects are briefly outlined in *Appendix A.*

PROCEDURE FOR PROGRAM FORMULATION AND EVALUATION

The procedure for formulating and evaluating a research program consists of two phases: (a) acquiring and validating the information, and (b) using the information in decision making. Phase 1 involves collection of data, updating and cross-checking of information while phase 2 deals with the conversion of data into a form usable for decision-making purposes. Portions of these operations can be designed to take full advantage of automated data processing capabilities (Rensi and Claxton 1972). Underlying the procedure there are assumptions as to what are the relevant data for the problem of research administration. Identification and classification of relevant data are based upon the model of a government research institution sketched in the previous section. Data can be organized under two main headings–data on individual research activities, and data pertaining to the organization as a whole.

Data on individual research activities can be classified as follows:

1. Identification
   a Identification code
   b Researcher in charge
   c Research target
2. Expected resource use
   a Time of completion
   b Budget expenditures
   c Use of other limited resources
   d Chances of completion
3. Expected utility contributions
   a Time series of economic benefits
   b Contribution to other performance criteria
   c Extra-economic adjustment factor
   d Chances of successful implementation
4. Documentation
   a Sources and references
   b Methods and assumptions

Item 1c, "Research target," is specified in such a way that it is possible at any time to unambiguously determine whether the research activity has been successfully completed. A research target can fall into any of four classes:

1. Collection, survey, or inventory of data
2. Classification of data
3. Formulation and testing of hypotheses
4. Development of technological applications

It is important to distinguish between the "target" of a research activity and the "applications" of a completed research activity. The research target refers to the "research phase" of the activity. The research phase may be followed by an "implementation phase," i.e., the conversion of research results into socio-economically useful applications. In some cases the "implementation phase" takes place outside the research unit or the research organization responsible for the "research phase."

In item 2c, "Other limited resources," are defined as resources other than budget monies which are available in limited short-run supply to the research organization. Item 2d, "Chances of successful completion," expresses the degree of confidence that the research activity will be successfully completed under time and resource uses as specified in sequences 2a through 2c.

Sequences 3a through 3d refer to one potential application of the research activity. Any additional application is documented likewise. "Economic benefits," as in item 3a occur when technical innovations are introduced into the industrial system to increase efficiency in production. They can be assigned either to new (improved) products and services or to new (improved) processes and methods. "Contribution to other performance criteria," item 3b refers to criteria other than economic benefits as such. Examples of criteria other than national wealth would be air pollution abatement, and reduction of urban congestion. Item 3c, "extra-economic adjustment factor," estimates the relative discrepancy between total public good and dollar value as determined through economic accounting. "Chances of successful implementation," is a measure of the degree of confidence that the application reported will generate the socio-economic utility described in 3a through 3c.

Data on the research organization as a whole describe the organization's restrictions and can be grouped as follows:

1. Projected budget limits.
2. Projected other limited resources limits.
3. Other performance criteria targets.
4. Internal allocation restrictions.
5. Interdependence restrictions.

This two part data classification scheme and its suggested subclasses is comprehensive in the sense that it covers all the elements that are relevant to decision making. It is also a flexible scheme since the data organized in such fashion can be used in the context of a variety of optimization techniques.

Acquisition and Validation of Information

Data Collection

Data pertaining to an individual research activity, such as that classified above, is produced in the process of preparing a "research proposal." A "research proposal" is the document accompanying the official request for funding of a research activity. Before being embodied into a formal proposal a given idea of a research activity is "kicked around" informally and, if necessary, modified until it appears to be by and large consistent with the perceived mission, scientific competence, and resource endowment of the research organization. The operations described above refer to a "new" research activity, i.e., a research activity which is being proposed for the first time. Conversely, a research activity is either "active" if it is currently going on, or "inactive" if it is on the waiting list. Data on the research organization as a whole are collected on a continuous basis as new information on organizational restrictions becomes available.

Updating Information

The information filed in the "dossier" of each research activity, as well as of the organization as a whole, is routinely updated on a continuous basis. Updating involves filling in information previously unavailable, and replacing obsolete data. Updating applies to new, active or inactive activities. The basic classification scheme remains intact; only the numerical estimates under each item are modified in the updating process.

Suppose, for example, that a breakthrough has taken place which will accelerate progress toward the accomplishment of activity X's research target. Then items 2a through 2d in activity X's file require updating. Another example: a discovery made in a competing field will render obsolescent the innovations attributed to activity Y. It is then necessary to reestimate items 3a through 3d in the "dossier" of activity Y.

Similarly, for the file of the organization as a whole, if new data become available on monetary budgets, resource availability, etc., the appropriate entries in the file must be revised.

The filing and updating scheme described is compatible with the requirements of automatic data processing. The speed and versatility of modern devices make it possible to handle a great amount of data and to reorganize the information in many different formats to suit particular needs or preferences. Thus a variety of updated reports could be produced to reflect the current status of a government research organization.

Cross-Checking Information

Part of the information filed consists of anticipation of future events. In some instances, value judgments and assessments of public priorities are explicitly or implicitly involved. Cross-check is a procedure by which anticipations and judgments are cleared, as much as possible, of inaccuracy and bias. Inaccuracy and bias may depend on vested interest as well as insufficient documentation. A thorough revision of the filed information is conducted, and estimates and measures are adjusted until they can be considered to represent the consensus of opinion or the best agreement of impartial, competent people. Generally, it is desirable to have the judgment of more than one expert, even if their opinions usually differ.

There are several ways to try for a consensus. One way is to gather the experts in one place, let them discuss the validity of the estimates, and require them to negotiate a joint answer. They could also be put to work separately, leaving to others the task of consolidating their findings into a joint assessment. Alternatively, experts could be invited to participate in group exercises ranging from structured discussions to more sophisticated techniques such as "operational games," "scenario writing," and "simulated debate" (Delphi method). Operational games involve role playing by individuals representing decision-makers in a simulated real world situation. Scenario writing is an exercise requiring experts to exhibit a reasonable chain of events through which a future state might be evolved from the given one. A collection of scenarios might provide insights into the likelihood of the occurrence of anticipated outcomes. In the Delphi method, direct panel debate is replaced as the means for the interchange of information and judgment by a carefully designed sequence of questionnaires. At each successive round, the participants are provided with more refined information representing feedback from previous rounds. The process continues until either a consensus is established or a dissenting view is fully documented.

The consensus-securing procedure to be adopted in any specific case depends on the type of organization involved. In general, the following considerations can be made. First, cross-checking consists of a thorough and complete review of an organization's list of research proposals. This process involves, at least for organizations over a certain size, a large amount of energy and effort. Consequently, cross-checking should be done once a year assuming yearly budget periods. The time of the year might be chosen to coincide with the period in which the current program is to be evaluated in terms of the past year's performance and the program for the new budget year is to be prepared. Secondly, different information items have to be established by different types of experts. For instance, item sequence 2a through 2d requires the consensus of competent scientific people in the research area considered. Estimates 3a, 3b, and 3d should be agreed upon by production and marketing specialists, who know the industrial sector affected by the application. Information under 3c should represent the agreement of a variety of interest groups, such as government, labor unions, and consumer groups. Thirdly, the process of cross-checking does not lend itself readily to automatic manipulation. Human judgment plays the major role in this process, and rightly so, given the nature of the task performed. Although the remaining steps of the procedure could be substantially automated, cross-checking would still have to be completed by, and under the control of, administrative personnel.

A possible use of the computer in cross-checking is to execute error-testing routines that can be applied systematically to spot possible areas of error. This warning method can be used to direct the attention of the auditors to estimates that may be suspect. For instance, if there is an exorbitant discrepancy between a project's cost requirements and its expected benefits, these estimates should be marked for further investigation and documentation.

Use of Information in Decision-Making

Once information has been collected and validated it can then be used for decision making. The techniques of optimization and analysis outlined here will enable the decision-maker to make full use of the information that is available. The conceptual framework established in previous sections enable him to consider optimization techniques that will select programs having known and desirable properties. Harnessing high speed computing capabilities to facilitate both data handling and optimization further provides a variety of analytical options (Rensi and Claxton 1972). This capability gives managers great power to explore, test, and validate their assumptions and opportunities, and to project and substantiate their organization's potential for growth and development.

An optimization technique discussed in *Appendix B* has proved to be a powerful tool for providing solutions with desirable properties. The integer programing technique suggested will also easily accommodate the complex formulation required to include important aspects of this decision-problem. The technique has proved to be sufficiently powerful in this respect that the restraining factor seems to be data availability rather than expression and manipulation of complex relationships.

The "Optimum" Program

A key result derivable from the information available is identifying the largest benefit attainable. Once the largest attainable benefit is identified, it can be used as the 100 percent mark for an efficiency scale against which any alternative program can be evaluated. Associated with the largest benefit is a program that produces the largest benefit, i.e., an optimum program. No other feasible program can be found with a larger benefit. An optimum program is also a feasible program, i.e., a program within the range of the organization's options as determined by the constraints. No alternative choice other than an optimum program can be justified unless the validity of the underlying model or the data are questioned; in other words, the finding of an optimum or best program is contingent upon the model of the organization selected and the validity data used. Different models of a research organization represent different statements and imply different measurements of objectives, activities, constraints and their interrelationships as illustrated in *Appendix A.* Consequently, each model involves its specific definition of optimum. Also, as noted above, even when the choice of the model is unobjectionable, the quality of the data used to implement the model may be such as to invalidate the identified "best" option.

An optimization scheme may be structured in such a way that the optimum solution generated consists of a set of binary decisions concerning each potential research activity. A zero-one integer programing formulation of this nature is described in *Appendix B.* A "yes" decision on a research activity may be interpreted as a recommendation that the research project be carried out. The opposite holds for a "no" decision. In this context a research activity is evaluated not only as a separate project on the basis of its own specific merits, but also in its relation to the over-all research objectives and resources of the organization. A research activity may consist of a new proposal as well as of an ongoing project. Activities representing ongoing research' are considered on the same basis as activities involving new research proposals insofar as only future resource requirements and expected contributions are taken into account. Past costs and benefits, "per se," are left out of the computations affecting future decisions. On the other hand, the "goodwill" element that may be associated with ongoing research pursuits is given adequate recognition in the data collection format proposed above to the extent that it is reflected in the estimates of "time of completion" and "chances of completion." The benefit of the optimum program represents an adequate parameter of the total worth of the planned activities of a research organization at a given time. Accordingly, it can be used to construct an index of the organization's present worth in terms of its potential for future results. Intertemporal comparisons of index magnitudes may offer an indication of the organization's position in its growth dynamic. Such indications may be used as an input for long-run policy decisions.

Analysis

A technique called "sensitivity analysis" is used to detect the sensitivity of the optimal solution to variations in the parameters of the problem. The more the optimal solution varies in response to a modification of a parameter, the more sensitive the solution is to that parameter.

This form of analysis is a powerful instrument for identifying factors that inhibit optimum effectiveness of the organization. Not only can major inhibiting factors be identified, but also the mode and the extent of their impact can be described and measured. Two measures seem to be of interest in the analysis. One, the most obvious, is the comparison of the total benefit derived from different values of the parameter under consideration. The other is the change in activity mix that results from changing parameter values.

The following suggestions do not presume to be exhaustive, but are presented to illustrate the potential of this method of analysis.

Constraint Removal or Relaxation

Adding and removing whole constraints may be within the power of the organization. Similarly the level of any restriction may be modified to a more or less desirable level. The over-all effects can be measured in terms of both effectiveness and the activity mix. The truth of the statement "we feel our organization would improve its performance if our budget were expanded" can be confirmed or rejected in a rigorous way by using sensitivity analysis. Possible limiting factors such as skilled personnel or equipment endowments may turn out to be real restrictions or merely specters. Restrictions with the strongest impacts can be identified. Internal restrictions, such as "each research division must be allocated an equal share of the total funds," or special objective restrictions such as "basic research projects must be allotted no less than one third of the total budget," may also have negative repercussions on the performance of the organization. In this case their modification or removal may insure a better balanced and over-all more efficient research program.

Benefit Sensitivity of Individual Activities

This approach is somewhat different from the previous suggestion. Here we ask the question, "How much variation in the benefit coefficient of each activity would be required to induce a change in the optimum program?" (Rensi and Claxton 1972). These results may be useful in directing additional effort into data validation. They may also be useful in suggesting research areas where alternative proposals would be valuable.

Additional Proposals for Activities

The validity of the entire analysis depends upon having available a large number of possible activities. Analysis may indicate that increases in resources would not result in a modified program. This condition may indicate a dearth of available proposals or a gap in the cost range of proposals. In either case, it would be helpful to increase the number or diversity of available proposals.

SUMMARY

Claxton, H. Dean, and Giuseppe Rensi.
1972. **An analytical procedure to assist decision-making in a government research organization.** Berkeley, Calif., Pac. Southwest For. and Range Exp. Stn. 20 p., illus. (USDA Forest Serv. Res. Paper PSW-80)

Oxford: 945.4--06.
Retrieval Terms: research administration; decision making; management planning; analytical procedure; mathematical models.

This report describes an analytical procedure to assist in management decision-making for a government research program. It proposes a model that, with its corresponding framework for data collection, provides a comprehensive means of considering many vital details of organization structure and operation.

It also provides the necessary flexibility for modification as learning advances and the organization is modified. The model provides a foundation for the optimization and analytical techniques described.

The objectives, activities, and restrictions of a government research organization are first considered, and a conceptual framework established. The major aspects that distinguish research from other forms of productive activities are examined at length. From this conceptual framework, the characteristics and potential uses of a management information system are suggested.

The proposed analytical procedure for formulating and evaluating a research program consists of two phases: (a) acquiring and validating information, and (b) using information in decision-making. In the first phase, data are collected, updated, and cross-checked. In the second phase, the data are converted into a form useable for decision-making. Some of the operations can be designed to take advantage of automatic data processing capabilities.

Most of the problems associated with decision-making in research are considered by the model, analytical methods, and data reduction techniques described. A carefully built data base coupled with the mathematical modeling and programing techniques exemplified in the appendixes can provide the research administrator with an effective and powerful analytical tool.

Computer programs developed to expedite data processing according to the specifications of the model and to perform optimization and analysis are described in a companion report, *A Data Collection and Processing Procedure for Evaluating a Research Program,* published as USDA Forest Service Research Paper PSW-81.

APPENDIX

A - Mathematical Formulations of Research Planning Problems

This appendix offers examples of mathematical formulations of planning problems in research. Several features that present a particular interest from the viewpoint of model building are discussed. For clarity of exposition and in order to avoid a plethora of symbols each feature is described separately as a potential refinement of a basic optimization model. The basic optimization model is outlined in the first example. The second example considers an extension of the primordial model to incorporate several heterogeneous research activities. The mathematical modeling of multidimensional benefits and the symmetrical case of multidimensional costs are examined in the third and fourth examples, respectively. The fifth example offers a mathematical statement of the problem of output interdependence, while the feature of time streams of costs and benefits is treated in the sixth. Finally, the seventh example demonstrates a formulation of the problem of uncertainty. The purpose of this discussion is to better assess the implication of each feature in terms of complexity of the analysis and information requirements. Once the basic model and each additional feature are thoroughly understood as separate building blocks it won't be difficult to formulate a model of research planning including any combination of the features outlined.

1. One Homogeneous Research Activity

Let the activity carried out by a research organization be represented by the production function

$$y = F(x)$$

in which y is a homogeneous output variable, say, ‘benefit’ and x is a homogeneous input variable, say, ‘cost.’ The production function is a set of maximum points. That is to each input point it associates the maximum output obtainable from it. Assume that a fixed budget B can be spent on research. Then the problem can be expressed as:

$$\begin{aligned} \text{max} \quad & y \\ \text{subject to} \quad & x \leq B \\ \text{and} \quad & y = F(x) \end{aligned}$$

A notion of optimum management policy is unambiguously defined in this formulation. A slight variant of it is

$$\begin{aligned} \text{max} \quad & (y\text{-}x) \\ \text{subject to} \quad & x \leq B \\ \text{and} \quad & y = F(x) \end{aligned}$$

in which net instead of gross benefits are considered in management choices. The shortcomings of these formulations are obvious. The definitions of input, output and function do not imply procedures for measuring them. They are unoperational. The causality relation between cost and benefit is assumed and not explained. And the definition of the production function as a locus of optimum points partially begs the question of the best decision. The decision problem is stated in a semi-tautological way.

2. Several Research Activities

Presumably the research activity carried out within an organization is not homogeneous, monolithic, and undifferentiated. A plurality of lines can be identified, each line characterized by different inputs, outputs, and relations between inputs and outputs. For example, compare a research on the microscopic properties of a species of wood and a research on the engineering properties of that species of wood when used as a construction material. By and large the two research lines have different input requirements in terms of scientific skills, equipment, and materials. Also the results are expected to be qualitatively and quantitatively different. One can then envisage a research outfit as a set of distinct research activities– each one of them characterized by a different production function. Assuming that inputs and outputs can be expressed in the same aggregate units of 'cost' and, respectively, 'benefit' for all of the N activities carried out then the production function of the jth activity can be specified as

$$y^j = F^j (x^j) \; ; j = 1, \ldots, N$$

Given a fixed a fixed budget, as in the previous case, the management decision can be stated as:

$$\max \quad \sum_j \; y^j$$

$$\text{subject to} \quad \sum_j \; x^j \leq B$$

$$\text{and} \quad y^j + F^j (x^j) \; ; j = 1, \ldots, N$$

If net benefit, instead of gross, were the appropriate performance criterion, then the problem can be restated as

$$\max \quad \sum_j \; (y^j - x^j) -$$

$$\text{subject to} \quad \sum_j \; x^j \leq B$$

$$\text{and} \quad y^j + F^j (x^j) \; ; j = 1, \ldots, N$$

Whether net benefit instead of gross benefit is used as optimality criterion depends on the possibility of using inputs in alternative ways. These alternative uses may include savings on consumption as well as alternative investment outlets. The solution of this type of decision problem involves the determination of the optimum set of values (x^j; j=1, . . . N) i.e., the set (x^j; j = 1, . . . ,N) at which benefit is largest. The technique of solution depends on the form of the functions F^j. If , $\sum_j F^j$ satisfies certain "convexity" properties and the budget constraint is expressed as an equality, [5] then calculus techniques, such as the method of Lagrangian multipliers, provide the mathematical conditions that the solution must satisfy. For the solution to make any sense at all, the magnitude of B must be consistent with a set of non-negative vectors (x^j ; j=1, N). If no particular restrictions are imposed on the form of the F^j's, then solution methods may be provided by iterative techniques. For instance, in a dynamic programing approach a recursion relationship expressing the optimality principle can be stated as

$$G^j (x^1, \ldots, x^N ; B) =$$

$$\max_{x^j} [(y^j - x^j) + G^{j-1} (x^1, \ldots, x^N ; B-x^j)]$$

where

$$y^j = F^j (x^j) \text{ and } O \leq x^j \leq B \; ; j = 1, \ldots, N$$

The relationship states that independently of the amount x^j of budget allocated to the j-th activity, the remaining portion of the budget $B-x^j$ must be distributed in an optimal way (in terms of net benefit) among the remaining (j-1) activities. As a final remark on this type of model note how, depending on the nature of the inputs and outputs of each activity, the operational specification of y^j, x^j and F^j;j=1,...,N may call for a prohibitive amount of information.

3. Multidimensional Benefits

If a research organization has several objectives whose degree of achievement is measured in different units, then it may be desirable to define benefit as a vector. Suppose that there are K-objectives. Then the output of the j-th activity can be specified as

$$\underline{Y}^j = (y_1^j, \ldots, Y_K^j)$$

Consequently the production function of the j-th activity is a vector function

[5] This is the classical example of optimum allocation described in textbooks of mathematical economics. See, for example, Hicks (1946).

$$\underline{Y}^j = \underline{F}^j(x^j) = \begin{matrix} F_1^j(x^j) \\ F_2^j(X^j) \\ \bullet \\ \bullet \\ \bullet \\ \bullet \\ F_K^j(x^j) \end{matrix}$$

The specification of multidimensional benefits raises a number of difficulties concerning the definition of an ordering of vectors. The solution of any decision problem is contingent upon the possibility of ranking alternatives according to some criterion and a vector criterion cannot generally be ordered. This problem can be solved by introducing a function that 'scales' the benefit vector, i.e., a mapping from the K-dimensional space to the real line. A special case of this function is a linear function

$$\underline{W}'\ \underline{Y} = \sum_K w_k\, y_k$$

where $W = (w_1,\ w_K)$ is a vector of weights specifying some hierarchical scale among the K benefit dimensions. In most instances, specifying quantitative equivalences between different objectives involves subjective determinations.

The decision problem can be stated in this case as

$$\begin{aligned} &\max && \sum_j \underline{W}'\underline{Y}^j\ ) \\ &\text{subject to} && \sum_j x^j \le B \\ &\text{and} && \underline{Y}^j = \underline{F}^j(x^j)\ ;\ j = 1, \ldots, N \end{aligned}$$

Another way to avoid the problem of indeterminacy or vector ranking in the multidimensional benefit case consists in selecting one benefit dimension to be maximized while setting minimum standards of achievement for the other benefit dimensions. This requires a redefinition of the activity production functions and a new specification of constraints. The problem can be restated as:

$$\begin{aligned} &\max && \sum_j y_1{}^j\ ) \\ &\text{subject to} && \sum_j x^j \le B \\ & && \sum_j y^j{}_k \ge \bar{y}_k\ ;\ k = 2, \ldots, K \end{aligned}$$

and

$$y_1^j = H^j(\,y_2^j, \ldots,\ y_K^j\ ;\ x^j)\ ;\ j = 1, \ldots, N$$

in which y_1 is the benefit dimension selected as maximand, $\bar{y}_2, \ . \ . \ . \ \bar{y}_k$ are the prescribed minimum requirements for the other benefit dimensions, and H^j are production functions with outputs $y^j{}_i$ which include $y^j{}_2, \ldots, y_k{}^j$ as parameters. The latter statement of the problem may be considered a subcase of the multiple input class of models to be treated in the next example.

4. Several Inputs

Instead of one-dimensional, all comprehensive measure of disutility one may specify several such measures. Hence an input vector $\underline{X} = (x_1\ ,\ x_M)$ is substituted for the scalar x. Introducing an M-dimensional input vector requires a reformulation of the constraints in the statement of the decision problem. Let the vector $b = (b_1, \ldots, b_M)$ specify upper bounds on the availability of the inputs. Let $\underline{P} = (p_1, \ldots, p_M)$ define the expenditures per unit for the M inputs, then the decision problem can be formulated as follows

$$\begin{aligned} &\max && \sum_j y^j \\ &\text{subject to} && \sum_j x^j \le b_i\ ;\ i = 1, \ldots, M \\ & && \sum_j (\,\underline{P}'\underline{X}^j\,) \le B \\ &\text{and} && y^j = F^j(\underline{X}^j)\ ;\ j = 1, \ldots, N \end{aligned}$$

in which $\underline{P}'\underline{X}^j = \sum_i p_i x^j{}_i$ represents the expenditure for activity j. The upper bound constraints need to be explicitly specified only for inputs whose availability is limited.

5. Output–Interdependence

It may be appropriate in certain instances to recognize explicitly the fact that the outcome of one research activity may depend on the outcome of other research activities. There are several ways in which this dependence can be specified in the definition of the production function for an activity. In general:

$$y^j = F^j(x^j\ ;\ (y^s\ ;\ s = 1, \ldots, N;\ s \ne j)\ )$$

i.e., the output of an activity is assumed to result from the interactive combination of the inputs of that activity and the outputs of the remaining ones. In some cases it may be warranted to hypothesize functional separability (Leontief 1947) between the input of activity j and the outputs of the other activities in the j-th activity production function.

Accordingly

$$y^j = F^j (x^j, G^j (y^s ; s = 1, . . . , N; s \neq j))$$

For example

$$y^j = F^j (x^j) \bullet G (y^s / \bar{y}^s)$$

states that the input productivity of activity j varies in proportion to the success in activity s measured as a fraction of a fixed output level $\bar{y}^s$. In other cases it may be appropriate to assume that in order for activity j to be carried out at all a certain level of output $\bar{y}^s \geq O$ must be reached in the other activities s = 1, . . . , N, s ≠ j. This situation can be represented by

$$y^j = F^j (x^j) \bullet G^j (\bar{y}^s ; s = 1, . . . , N ; s \neq j)$$

$$G^j (\bar{y}^s ; s = 1, . . . , N; s \neq j) = \begin{cases} 1 \text{ if, for all s, } y^s \geq \bar{y}^s \\ 0 \text{ otherwise} \end{cases}$$

6. The Time Dimension

As time is introduced in the analysis, the inputs and outputs of a research activity are treated as time streams. Let

$$\underline{X}^j = \{ x^j_i, x^j_2, . . . , \text{and } \underline{Y}^j = y^j_1 \; y^j_2 , , , , .\}$$

represent streams of yearly inputs and outputs, respectively, for the j-th activity. Assuming that each yearly flow y_t^j , t = 1, 2, ..., is measured in dollars, the present value of the output stream Y^j can be defined as

$$y^j = \sum_t y^j_t d^t$$

where

$$d^t = (1 + \rho)^{-t}$$

and *p* is an appropriate rate of interest. For every $\underline{X}^j$ consider the highest present value of all output streams $\underline{Y}^j$ that could be produced from $\underline{X}^j$. The pairs of y^j $\underline{X}^j$ so defined constitute the 'time production function' for the j-th activity, namely,

$$y^j = F1 \text{ (Xi)}$$

The time production function so defined depends on the fixed parameter *ρ*. To express this dependence the function can be stated as

$$y^j = F^j (\underline{X}^j ; \rho)$$

In some cases one may be justified in assuming that the value of the output stream of a research activity *discounted to the time of successful completion of the activity* is a constant. This assumption corresponds to the notion that the output of a research activity is a specific scientific target. When evaluated from the vantage point of the present, the potential repercussions of a specified scientific achievement or a technological innovation have a fixed magnitude. [6] Define this constant value as $y^j{}_*$, the 'potential' of activity j. What varies as a function of the input stream is the time of completion of the research activity. Let t_j be the time of completion for activity j. Then

$$t_j = G^j (\underline{X}_j) \text{ and}$$

and

$$y^j = y_*{}^j d^{t_j} = y_*{}^j d^{G^j (\underline{X}^j)}$$

represent simple statements of the production constraints. When time is introduced in the statement of the decision model, budget constraints and constraints on other limiting factors must be specified for every year of a future time horizon of appropriately chosen length H. The decision problem could then be specified as

$$\text{Max} \quad \sum_j y^j$$

$$\text{subject to} \quad \sum_j x_t^j \leq B_t ; t = 1, . . . , H$$

$$\text{and} \quad y^j = F^j(\underline{X}^j ; \rho)$$

where B_t is the budget constraint for year t. Here, as well as in example 5 simple one-input, one-output activity production functions have been presented for simplicity of exposition and economy of symbols. The extension to several outputs and inputs dimensions along the lines suggested in Examples 3 and 4 respectively, can be easily made.

7. Uncertainty

A decision model may contain assumptions concerning the problem of uncertainty. This is especially

[6] What is assumed here is a time schedule of implementation and diffusion of the socio-economic consequences of the scientific achievement independent of the amounts of inputs invested in the research phase; that is, the research outfit has control only on the production of research results and not on their adoption in productive uses.

appropriate in a research activity in which input-output relations cannot be known with certainty, or if future constraint bounds may not be specified with perfect knowledge. In either case stochastic mechanisms can be included in the model by substituting

$$y^j = F^j (x^j) \qquad j = 1, \ldots, N$$

with $$y^j = G^j (F^j (x^j), u^j) ; P^j (u^j)$$

$$j = 1, \ldots, N$$

and $$\sum_j x^j \leq B$$

with $$\sum_j x^j \leq H(B, v) ; Q(v)$$

where G and H are functions to be specified and u^j j=1, . . . ,N, and v are random variables with probability distributions $P^j(u^j)$, j=1,...,N, and $Q(v)$ respectively. In the case when the time variable appears in the model it may be appropriate to consider time vectors of random variables

$$\underline{U}^j = (u_1^j, u_2^j, \ldots) ; j = 1, \ldots, N$$

joint probability distributions $\Omega(\underline{U}^j)$.

As a specific example, consider the stochastic production function

$$y^j = F^j (x^j) \bullet u^j ; O \leq u^j \leq \infty ; E(u^j) = 1$$

Here only the range and the expected value of the probability distribution of u^j are specified. This stochastic representation of the production function for the j-th activity reflects the fact that for a given value x^j of the input variable, the output obtained is not precisely $F^j(x^j)$ but more or less $F^j(x^j)$ i.e., $F(x^j)$ multiplied by a variable whose expected value is one. If $u^j > 1$ the success of allocating x^j to the j-th research activity will have been greater than 'expected' and vice versa.

Instead of 'objective' probability distributions with parameters to be estimated from empirical data, one can specify subjective measures of confidence to be used as the certainty equivalence factors mentioned toward the end of the section on Activities and Programs.

B - Zero-One Integer Programing Optimization

This appendix describes how the zero-one integer programing optimization technique can be used to select a best research program among several alternatives. At the same time it demonstrates how the data identified and classified in the section Acquisition and Validation of Information can be used as input for the optimization model.

Consider the list of activities which are candidates for inclusion into a research program. Assume the total number of these activities to be N. Let each activity be labeled with an index number i, where i goes from 1 to N. Define the following measures for each activity:

T_C = completion time, i.e., number of remaining budget years for the research activity.
T_B = beginning implementation time, i.e., number of years from the research inception after which the results of the research will be first applied for useful purposes
T_E = ending implementation time, i.e., number of years from the research inception after which the application of the research results will be discontinued because of obsolescence
P_C = chances of successful completion of the research activity
P_I = chances of successful implementation of the activity, given its successful completion
x_t = research budget for year t, where t goes from 1 to T_C
y_t= net benefit, i.e., dollar benefit minus implementation cost for year t where t goes from T_B to T_E
r = interest rate to be used in the discount formula
w = extraeconomic adjustment factor

Given these information items for a research activity the benefit of the activity can be calculated as

$$b = \left(\sum_{t=T_B}^{T_E} y_t (1+r)^{\,t} \right) P_c P_I w \quad \sum_{t+1}^{T_C} x_t (1+r)^{\,t}$$

Let the benefit for activity i, calculated according to formula (1), be indicated as b_i

Suppose M constraints are specified for the organization, labeled j=1, 2, 3, ..., M. Let U_j represent an upper bound measure of the j-th constraint and a_{ij}, i=1, ..., N, measures of how research activity i,i=1,....

N is affected by the j-th constraint. With reference to the section, Constraints, four types of constraints can be considered, namely limited resource constraints, minimum performance constraints, internal allocation constraints, and interdependence constraints. Consider instances of each type of constraint.

1. Limited Resource Constraints

Let constraint j reflect a limitation on budget money in year t. If the expected budget for the research organization in year t is expected to be X_t and the planned money expenditure for research activity i in year t is x_{it} then, for constraint j, $U_j = X_t$ and $a_{ij} = x_{it}$; i=1, ..., N. Similarly let constraint j represent limited availability of a certain physical facility. If H is the number of weekly hours when the facility is available and hi is the number of weekly hours requirement by activity i, then constraint j is defined by $U_j = H$ and $a_{ij} = h_i$; i=1, ..., N.

2. Minimum Performance Constraints

Let constraint j define the requirement that the organization achieve at least G units of a certain special goal. Let g_i represent the number of units of the goal that activity i is expected to achieve. In this case $U_j = -G$ and $a_{ij} = - g_i$; i=1, ..., N.

3. Internal Allocation Constraints

Let constraint j express the requirement that at least X_D dollars be spent on an administrative subdivision D of the organization in year t. Then $U_j = -X_D$ and $a_{ij} = -x_{it}$ if activity i falls under the jurisdiction of subdivision D, a_{ij}= O otherwise, i =1, ..., N.

4. Interdependence Constraints

Let constraint j specify the fact that activities belonging to a specified subset S are mutually exclusive. Then one may set $U_j = 1$ and $a_{ij} = 1$ if activity i belongs to S and a_{ij} = O if activity i does not belong to the specified subset.

The information on benefits and constraints as outlined above can be summarized in a compact form as shown in *figure 4.*

Given a set of N activities

$$T= [1, 2, ..., N]$$

any subset of T represents a program. For instance

$$P= [i_1,i_2, . . . ,i_K]$$

where $K \leq N$ is such a program. The benefit of a research program so defined is the sum of the benefits of the activities included in the program, i.e.,

$$B = \sum_{i \varepsilon P} b_i = \sum_{k=1}^{K} b_{i_k}$$

Similarly the program's requirement of constraint j is the sum of the requirements for constraint j of the activities included in the program, namely

$$R_j = \sum_{i \varepsilon P} aij = \sum_{k=1}^{K} a_{i_k j}$$

Given the upper bounds on the constraints, U_j; j=1, . . . ,M, a program P is called feasible if, for all j, j = 1, . . . ,M

Figure 4—Example of information requirements for a zero-one integer programing formulation of research planning.

Activities	Benefits	Constraints 1	2	3	. . .	M
1	b_1	a_{11}	a_{12}	a_{13}	. . .	a_{1M}
2	b_2	a_{21}	a_{22}	a_{23}	. . .	a_{2M}
3	b_3	a_{31}	a_{32}	a_{33}	. . .	a_{3M}
4	b_4	a_{41}	a_{42}	a_{43}	. . .	a_{4M}
.	.	.	.	.		.
.	.	.	.	.		.
.	.	.	.	.		.
.	.	.	.	.		.
.	.	.	.	.		.
N	b_N	.	.	.		a_{NM}
Constraint upper bounds		U_1	U_2	U_3	. . .	U_M

$$R_j \leq U_j$$

i.e., if none of the program constraint requirements exceeds the constraint availability bound. Conversely a program P is unfeasible if it violates at least one constraint, i.e., if for at least one j

$$R_j > U_j$$

The zero-one integer programing approach to selecting an optimum research program consists in finding a program P* which yields the largest benefit among all feasible alternatives. In other words one wants to find P* such that

$$\text{(a) } R_j (P^*) \leq U_j \text{ ; } j = 1, \ldots, M$$

and

$$\text{(b) } B(P^*) \geq B(P)$$

where P is any feasible alternative program. Analogously the problem can be specified by defining for each activity i; i=1, N an index variable

$$I_i, \ i=1, \ldots, N$$

indicating whether activity i is included in a program or not. If research activity i is included in the program examined $I_i = 1$, otherwise I_i=O.

The problem can then be stated as follows:

$$\max_{I_i} \quad B = \sum_{i=1}^{N} b_i I_i$$

$$\text{subject to} \quad \sum_{i=1}^{N} aij\, I_i \leq U_j \text{ ; } j=1, \ldots, M$$

To understand what the solution of the problem entails consider the following elementary solution algorithm

(i) List all possible alternative research programs, i.e., all subsets $P \subseteq T$
(ii) For each alternative program calculate the total benefit and constraint requirements
(iii) Discard unfeasible programs
(iv) Of the remaining programs select the one with the largest benefit as best.
(v)

This is a perfectly valid solution method in the sense that it will always produce the best program. However it is a computationally inefficient method especially if the possibility set consists of a large number of activities. The reason for this is that if N is large there is an extremely large number of programs to be screened one by one for feasibility and optimality. In fact given N possible activities in the candidate list there are $\binom{N}{1}$ one-activity programs, $\binom{N}{2}$ two activity programs, . . . $\binom{N}{N}$ activity programs.[7] Summing all these possibilities one obtains

$$\sum_{K=0}^{N} \binom{N}{K} = 2^N$$

Noting that for N=10, 2^N equals 1024 and for N=100, 2^N equals approximately 10^{30} one can readily appreciate the magnitude of the computational effort involved and the necessity for an efficient solution algorithm.

For the purposes of this study a fairly satisfactory zero-one integer programing solution method has been assembled and experimented with on a variety of numerical problems. A detailed account of the algorithm and its properties is beyond the scope of this presentation. It is a branch and bound type of algorithm and it applies theoretical results developed by Balas (1965) and Glover (1965) with modifications to take advantage of the special structure of the research activity selection problem.

7 $\binom{N}{K}$ is the number of combinations of N objects taken K at a time. $\binom{N}{K} = \dfrac{N!}{K!(N\ \ K)!}$

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