SOME SYSTEMS STUDIES OF THE INNOVATION PROCESS (RESEARCH - DEVELOPMENT - INTRODUCTION)

Abstracted by
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PREFACE

This working paper consists of extracts from research studies of the innovation process, development and introduction, undertaken in the USSR, Hungary and the USA. They were selected and abstracted by Gennady Dobrov, Peter Vas Zoltan and Robert Randolph as part of their general research on the science of policy analysis. Since these studies are not generally accessible, it has seemed worthwhile to make them available to collaborators in the IIASA Innovation Task, and others, in the form of a working paper.

We are grateful to Kan Chen, Vladimir Pokrovsky and Edward Roberts for permission to reproduce their material.

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NATIONAL RDI POLICY MACHINERY

In all countries the investigation, creation, transfer, and utilization of techological innovations is directed or at least influenced by the following types of actors:

- organs of legislative and executive state power;
- leading organs (associations, etc.) in various social and economic sectors;
- the leaders of the organizations and collectives (institutes, firms, etc.) involved in the process of technological development; and
- various communities and groups of people concerned with science and technology or with use of possibilities connected with this.

Of course, the social essence of this complex process is different in different countries (especially the systems of values, criteria and preferences which determine the goal function and character of managerial decisions, and also the systems which are used for stimulation of the process of technological activity itself). Also different are the organizational structures and procedures of decision-making organs. Often there are grounds for discussing these as fundamentally different, mutually competitive, or contradictory to one another in some regard. This happens not only in the case of international analysis, but also on the scale of each country being examined.

Nevertheless, the experience of managing technological development which has been accumulated and is being accumulated in various countries allows us to distinguish some general systems characteristics of this process.

Figure 1 presents a generalized scheme of the interaction among the basic elements of the structure for management of national RDI activity. In the terms adopted by UNESCO, this is a "cybernetic model" of the national RDI system. Following the recommendations of the Science and Technology Policies Division of UNESCO, this model is used in the analysis of systems for management of RDI activity that have been established in various countries, and also in the designing of such systems for developing countries.

Among the characteristics of this mechanism are the following:

1. managerial functions are separated between the levels of legislative and executive power, direct production of technological results, and their practical use (from which data about the consequences of technological activity are obtained);

2. fundamental significance has to be given to the effective functioning of developed feedback channels for transmission of data about the dynamics and qualitative structure of technology;

3. the system must include well-developed services performing the "memory" function--the accumulation and systematization of data about the needs, potential, activity, and results of technological development;

4. decisions made at all levels of management must take account of the significant time-lag which exists in the system between "input" and the signals really received through the feedback channels, in view of which the management information must include specially future-oriented assessments.

The experience of many countries, and the science policy studies, show that failure to meet any of the indicated demands for RDI management leads to a sharp reduction in its effectiveness. In all known cases, losses from incomplete use of technological possibilities exceed the colossal economic and social benefits which society receives from technological progress. Duplication of technological work, deceleration of the RDI cycle, irrational structuring of efforts, and failure of science and education to meet national needs--all these are examples of direct losses. Growth of the gap in levels of development of various countries, delay in the "substitution" and utilization of new resources, and unforeseen negative ecological and social effects--these are examples of losses which may affect many generations of people, ideas and things. It is to avoid these hazards that efforts are under way to improve the analytically based management of research, development and introduction of socially organized technology, and thus that RDI policy studies has been recognized as an important branch of applied systems analysis. A philosophical approach to this subject has been developed in papers by Dobrov et al (1978) and Schumacher (1973). The studies outlined in the rest of this paper illustrate the work that has been done in different countries.

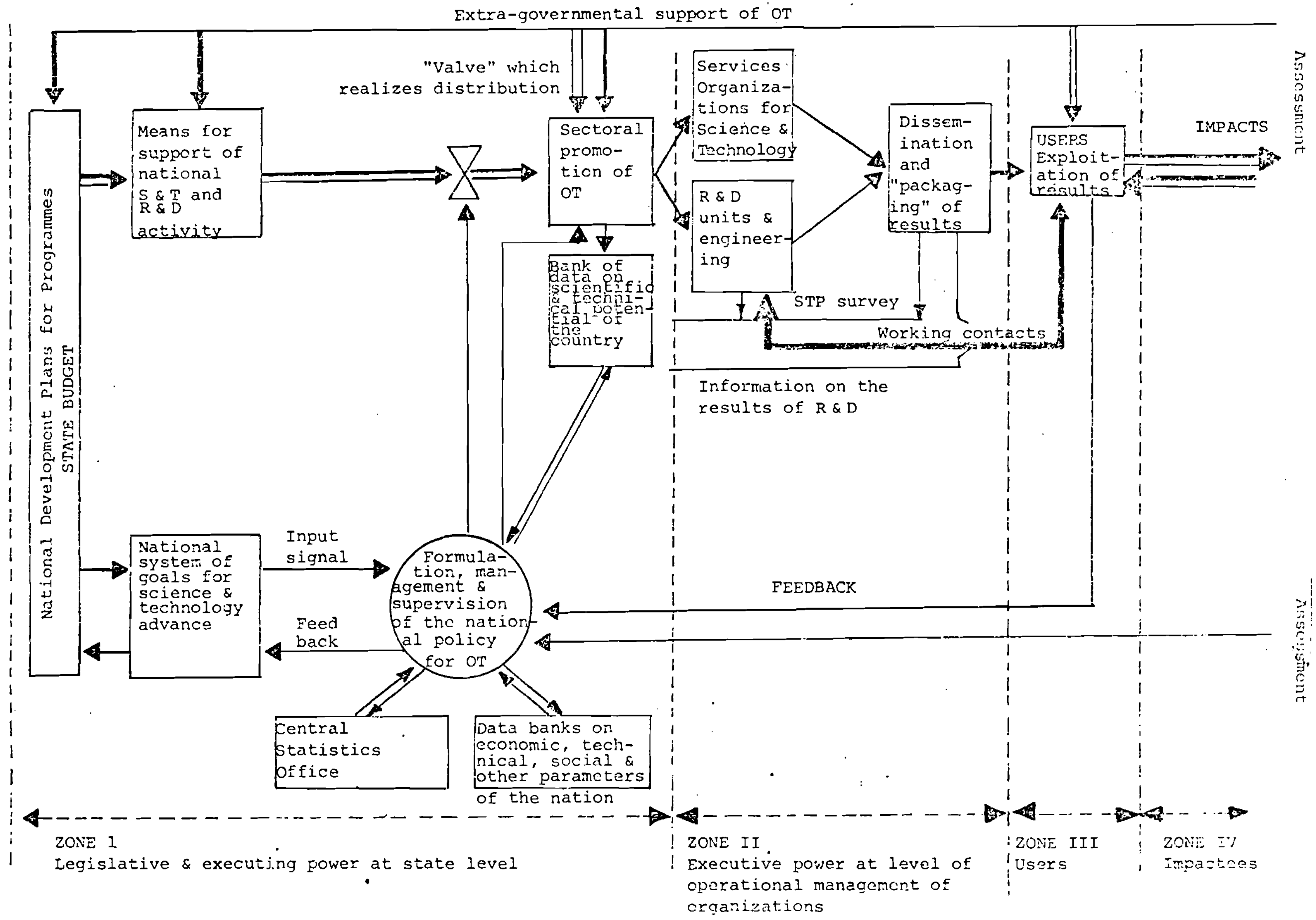


Figure 1. Generalized scheme of the interaction among the basic elements of the structure for management of national RDI activity.

THE PATTERNS OF APPLIED RESEARCH-DEVELOPMENT INFORMATION POLICY ANALYSIS

A Model of the RDI Life Cycle

The set of interconnected activities involved in the innovation and production process, together with the related managerial actions, compose a special system called the "life cycle of organized technology". Especially on the industrial level of decision making, these life cycles of creation, implementation, and eventual replacement of technological systems are--or have to be--a main object of RDI policy.

A general description of such a cycle is given in Figure 2. The following quantitative assessments which can be added to this picture stem from world-wide industrial experience.

1. As a result of crucial changes in the average annual rate of technological substitution (3-4% before World War II, 8-10% in the 1970s--including 20-25% in science based industries) the need for "long-range effective" technological systems (i.e., systems which will not soon become obsolete) is becoming every more urgent;

2. As a result of the growing complexity and "science-content" of technological changes, the time and cost of the R & D parts of the technology life cycle are increasing. During the 1970s, the statistically estimated duration of projects increased by 1.3 to 1.5 times and their cost--more than twice;

3. As a result of the growing interdependences between RDI and socio-economic factors, the time spent on systems analysis and decision making in the management of RDI tends to increase. Known data together with our observations show that the total time of waiting for managerial decisions (T_D) can in some cases exceed the total duration of all other actions in the life cycle. The average estimation for all cases is:

   $$\sum T_D = ({}^1/4 \div {}^1/_3) T_{L.C.} \quad ,$$

   where $T_{L.C.}$ represents the overall time-length of the life cycle. Contemporary estimates of the typical proportions of total cost and time spent on various stages in the life cycle of technology are given in Table 1. The table which is based on assessments by G. Morgenthaler (1973), generally follows our empirical findings (see Dobrov 1970).

Nationally supported technology transfer--e.g., an active patent and licence policy, international cooperation and technology exchange--are important for all countries as an effective option in dealing with the above-mentioned constraints. There is data

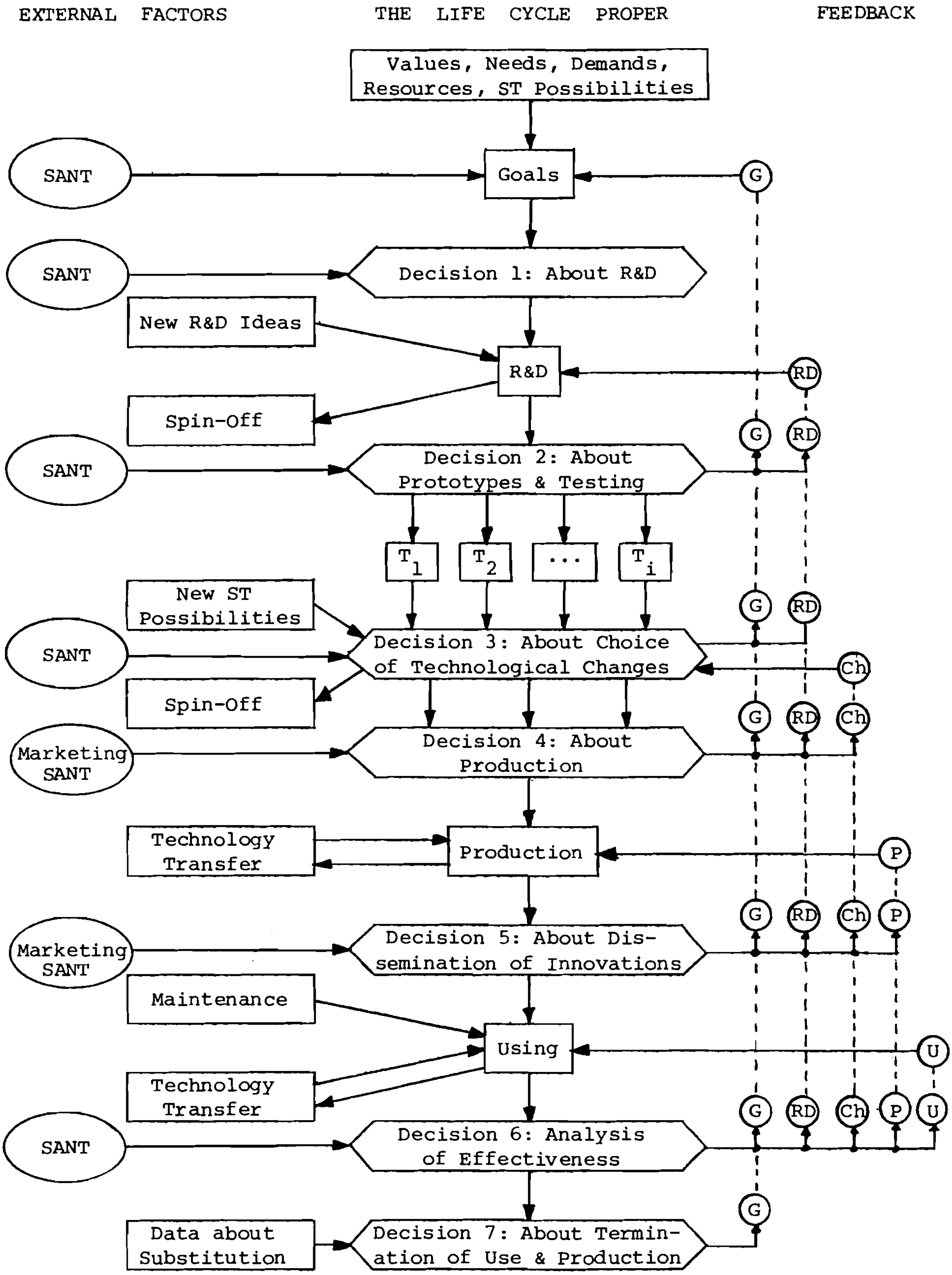


Figure 2. The life cycle of technology.

Table 1. Estimation of the structure of efforts in the life cycle of technology.

Stage			Cost (%)	Time (years)
INNOVATION		Goal setting	1	?
		Research	5-10	2-3
		Development	10-20	1-2
	INTRODUCTION	Preparation for production	40-60	1
		Organization of manufacture	5-15	1
		Organization of market	10-25	1
Total			100	6-8+

that if all available RDI information were utilized, this would be equivalent to at least a redoubling of efforts in research, development and technological innovations. Technologically developed countries also have useful experience in solving problems in other ways: MBO (Management by Objectives, PPBS (Planning Programming, Budgeting System), Selection of Portfolios of R & D Ideas, Technological Risk Evaluation, etc.

The USSR has experience in the long-range and operative planning of R & D and goal-oriented programs of technological advancement where managerial efficiency is increased by applying the set of systems demands--"sped-up", "wide-spread" and "complete" utilization of available final and intermediate R & D results. The main benefits of this approach are: increasing the quality of technological options, reduction of time for the innovation period by 1.5 to 1.8 times, and diminution of the volume of non-applied results by 4-5 times.

Figure 3 illustrates the dynamics of outflows and incomes which together determine the final "effectiveness" of the technological life cycle. Some conclusions important for RDI policy stem from international experience in the management of such cycles:

a. In the course of time, the more advanced the situation is in the life cycle, the more important is the role of organized transfer and use of intermediate technological results ("spin-offs"). Very often research which has started from basic studies can give concrete results utilizable in related areas (and so justifies itself) even before the entire RDI project reaches its main intended result.

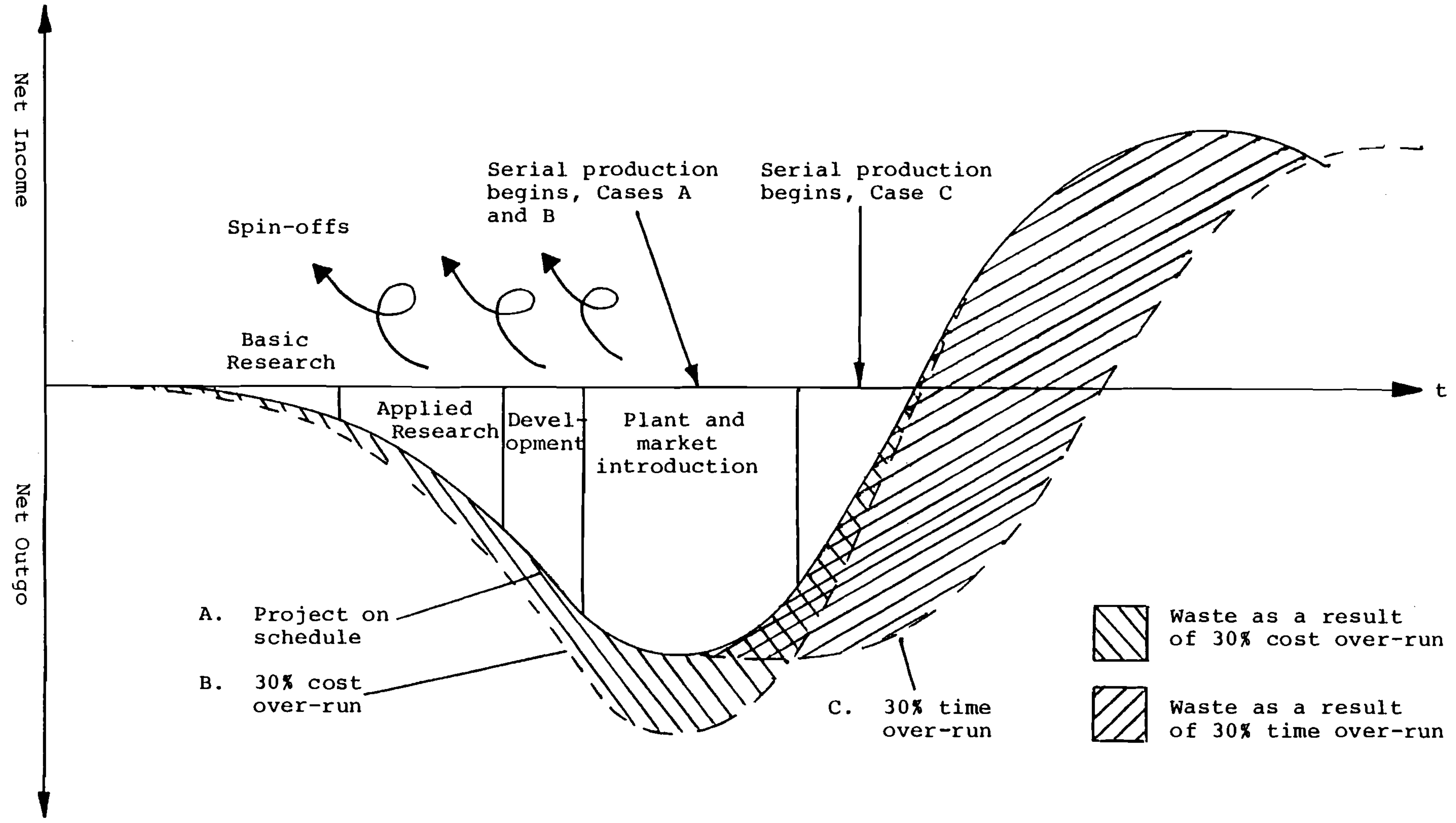


Figure 3. Net income or outgo during each year in a typical RDI cycle, showing effect of cost and time over-runs.

b. The final economic result of managing the life cycle differently depends on the unavoidable errors in previously made estimations of the cost and the time of work to be fulfilled.

The risk of mistake in timing leads not only to additional outflow but also to postponement of returns and diminution of the time of future utilization of the given technology before it becomes obsolete.

One of the general rules of RDI success is--"to be on time". The importance of this rule can be illustrated also with the help of the model described in Table 2. It shows the interrelations between the main controllable variables of RDI management. This model also helps to substantiate the following rules for an effective RDI policy:

-- to keep up the tempo of RDI work;

-- to secure as complete as possible utilization of any intermediate applied findings;

-- to achieve widespread dissemination of final technological results.

In order for this set of rules to be comprehensive, additional attention is needed to the <u>quality</u> of RDI actions and results. It is known that as an RDI project progresses from one stage in the technological life cycle to the next, each unit of RDI work becomes more capital intensive by approximately an order of magnitude. So, if a mistake in research demanding for its correction only one unit of investments ($, R, Fr. ...) is not corrected, during the next RDI stage (development) it will need about ten units of money, and during the stage of introduction it will cost 100 units. Being not corrected here, the mistake will require already about 1000 units of investments for correction when the technological system is in the user's hands.

It is possible to generalize this entire set of systems recommendations for RDI policy-making as a <u>logical formula of success</u>:

$$(> S + > W + > C) \times Q \rightarrow Ef_{rdi} \quad ,$$

that is,

$$\left.\begin{array}{l}\text{"More Speedy"}\\ \text{"More Complete"}\\ \text{"More Widespread"}\end{array}\right\} \times \text{ High Quality } \xrightarrow{\text{yields}} \begin{array}{c}\text{Effectiveness of}\\ \text{RDI}\end{array}$$

Table 2. Return of investment in technology advance.

$$\gamma = \frac{E_{(i)} \cdot t_{us} \cdot \bar{N}}{\bar{q}_{rd} \cdot t_{rd} \cdot k + \bar{q}_{int} \cdot t_{int} \cdot N^*} \quad ; \quad \left[\frac{\text{units of output}}{\text{units of inputs}}\right]$$

where:

$E_{(i)}$ = effect of using new technology system for one year

t_{us} = time for use of this technology before substitution

$\bar{N}$ = average number of technological systems in operation during time, t_{us}

$\bar{q}_{rd}$ = average cost of one year of R&D for preparation of this technology

$\bar{q}_{int}$ = average cost of one year of the process of plant and market introduction of this new technology

N^* = number of introductions needed for transfer of this new technology

t_{td} = time of R&D needed for preparing this new technology

t_{int} = time needed for introduction of one technological system

k = coefficient of multiplication and proportion of unsuccessful R&D projects ($k > 1$)

($k = 1$, if we have a single successful project;
$k = m$, if k is a multiplicative factor).

At this point it may be useful to note that the practice of Systems Assessment of New Technologies (SANT) based decision making has an effect on the necessary structure of information gathered and processed in SANT itself. One criterion for the information content of SANT is that it must correspond to the informational structure of the decisions. And one good way of analyzing this structure is in terms of the morphological box presented above.

A Methodology for Measuring and Managing RDI Efficiency

The examination of efficiency and effectiveness is by no means a purpose in itself. It can serve not only as the indicator of the degree of the effect (which can be expressed in a percentage) but also, and this is more important, as a basic means of RDI management, of science-policy and in the last analysis of correct decision making in economic policy. Only when one is fully aware of the efficiency of research activities in the various disciplines of science, can investments be allocated reasonably, the ratios of financing be established, technological norms and standards be optimized and, eventually, the effects resulting from RDI achievements be integrated into economic planning.

Efficiency means the proportionate relation of the results of expenditure. It is a "concept intrinsic to science and technology which measures how far resources invested in research and development have been productive within reasonable time limits" (Unesco 1978). Or, "efficiency is the ratio of useful work performed to the total energy expended" (The Concise Oxford Dictionary 1972). The effectiveness of RDI system can be interpreted as an assessment of how the system as a whole as well as its different parts are functioning in relation to the objectives and principles laid down for the system. Or, "effectiveness is a concept intrinsic to science and technology, which gauges the output of R & D both qualitatively and quantitatively against the socio-economic goals or objectives pursued" (Unesco 1978).

There are two aspects to be discussed in connection with efficiency (i) how to evaluate and measure efficiency? (ii) how to manage its increase? The present section is going to deal with the first problem.

Efficiency is a secondary notion since an antecedent, i.e., an effect triggered off by actions is needed for its existence. Therefore, we can only define it if we set out from the analysis of the effect.

All RDI activities have some effect which generally indicates a number of directions. Even research ending in failure has certain effects: namely, it provides negative information indicating the direction to which it is not worthwhile to conduct research. If certain research has proved fruitful and has had some effects, one of the following categories of effects will become characteristic. These categories may be classified in four groups:

1. The scientific-informative effect, which enriches knowledge, serves as a starting point for further research, and is sometimes integrated into the official curricula.
2. The social (political, ideological, cultural, etc.) effect, which becomes a material force in the life of society, without resulting in any direct or indirect economic benefit.
3. The defence effect, which is a characteristic of military research.
4. The economic effect, which contributes directly or indirectly to the growth of national income and is a concrete measure of how science is becoming a productive force.

These four categories of RDI effects cannot and should not be compared to each other as they are incommensurable. It is the theme, the aim and the type of research together that determine the most desirable effect-category. Hence, the value of any research project cannot be determined by any of the characteristic effects in itself. However, if the economically exploitable result is of prime importance, then the examination of the economic effect and efficiency should be the basic guideline for making decisions.

There are various approaches to the examination of the efficiency of RDI. The non-economic approaches attempt to quantify the qualitative factors, namely,

1. Sociological survey of the RDI environment, the analysis of factors influencing RDI.
2. The evaluation of qualitative determinants according to point-values; that is, the characteristic features of the phenomenon examined on the basis of various criteria are given variable point-values, and so it becomes possible to choose the most appropriate variant out of the combination thus gained. This approach makes it possible to rank the RDI subjects and to choose the adequate variant.
3. The sciento-metric approach: on the basis of collected data, the science citation index shows how frequently a first author is cited in literature. The statistical results of this can then be analyzed by various methods. For the evaluation of efficiency there are also economic approaches.
4. Profitability calculation, which must be made parallel with efficiency evaluation, since the degree of profitability does not express efficiency, as it may increase without any growth in the latter.

5. Calculations in licence equivalents, which, being another indirect analysis of RDI efficiency, indicates how much more expensive or economical domestic production may be than the purchase of licences or know-hows.

6. The examination of the economic efficiency of RDI activities characterized by their economic effect, i.e., the calculation of the economic efficiency of RDI in such cases where the economic effect is directed towards one of the production factors: implements, object of labor, technological processes, forms and methods of managing production and labor etc.

If we compare the expenditures invested in a given process with the desired and/or achieved economic result, then it is the absolute economic efficiency we are trying to examine. If, however, we compare the planned result with the achieved one or the economic efficiencies of the different variants, then we are examining the relative economic efficiency.

We can speak of the economic efficiency of RDI on the macro (national economic, global) level when the contributions of all RDI activities of a country to national income (of GNP, GDP) are taken into consideration; however, even in this case it must be borne in mind that not all RDI activities have economic effects. And we may speak of it on the micro (individual, singular) level when we are examining the turning of the idea into use-value, i.e., the work of one researcher, one institute, one team, or the improvement of one product, etc.

Calculations of economic efficiency indicate the capacity of RDI in a general way. Efficiency evaluations lead to direct conclusions as regards the future and they may be applied either in a narrow range or on a national scale. For us, the evaluation of economic efficiency represents the most comprehensive approach. Of course, every approach has its specific features, advantages and characteristic information content. However, this information will only become meaningful if, in addition to providing the facts and indicating the conclusions concerning the future, it also enables us to improve RDI activity by means of further measures, and if it can be used in decisions on the level of science and technology policy management. In other words; if the information becomes manageable and serves as a basis for decision making.

The theory and the computational practice of economic efficiency has immense literature; several hundreds of formulae and methods of calculation have been worked out in order to compile the various efficiency indices, all expressing different viewpoints.

Our second question "how to manage the increase of efficiency?" requires a systems analysis approach, as its management comprises an entire system of means and methods. The growth of science in our days demands an elastic system of various measures, since only such a system is able to increase the efficiency of the RDI institutions. This complex can be summarized (see Trapesnikov 1977) as shown in Table 3.

One special problem currently being addressed in systems-analytic studies of the technological life cycle is that of determining what fraction of the overall benefit (profit, etc.) produced by a new technological system is properly ascribable to each of the organizations involved in its development and use, or more generally to each of the main spheres of activity involved in the life cycle (i.e., the spheres of R & D, production, and operation). Underlying this problem is the fact that in most cases, the sphere which created the possibility for emergence of the effect (e.g., the R & D sphere) does not coincide with the sphere where the effect is ultimately obtained (e.g., the sphere of final operation). (According to data from the USSR Central Statistical Administration, roughly two thirds of the effect arises in final use (Pokrovskii 1978).

Many approaches to the allocation of benefits among the various spheres and organizations are conceivable, based on prices, "value added", etc. But most such approaches are applicable more to one type of economic system than another (capitalist, centrally planned, etc.). However, V.A. Pokrovskii in his recent book on Raising the Effectiveness of Scientific Research and Development (1978) offers a simple yet effective solution to this problem which should be widely applicable, with a case-study example based on an actual R & D program in the Soviet mass transport industry.

Analysis in the case Pokrovskii describes was begun in 1960, when the system in question was still in the R & D stage. As development of the system progressed, comparisons were made between forecasts of cost and "economic effect" made by various methods and also between forecasts and the actual cost-effect trends as they evolved. It was found that forecasts were usually accurate within ±6-7%, only rarely erring by as much as 20%. As it turned out, Pokrovskii says, final R & D costs were 1.41 million rubles less than had been predicted. The time-trends in costs and economic effects (and forecasts of these for the remainder of the technology's expected life) were as shown in Figure 4.

Using this particular technology as a sample case, Pokrovskii suggests that recommendations about the distribution of economic effects of new technology among the involved sectors can be based on estimates of the share of "creative" work in the overall expenditure of labor time in each sector. Investigations of the use of labor time, he says, have shown that creative processes occupy 60% of total labor time in R & D, and 25% in serial production or in operation of the finished technology. Thus a "coefficient of creativity" (K) can be assigned to these three sectors in the proportion 60:25:25, or equivalently 2.5:1:1.

Then the division of economic effect among the three sectors can be assigned according to the following formula:

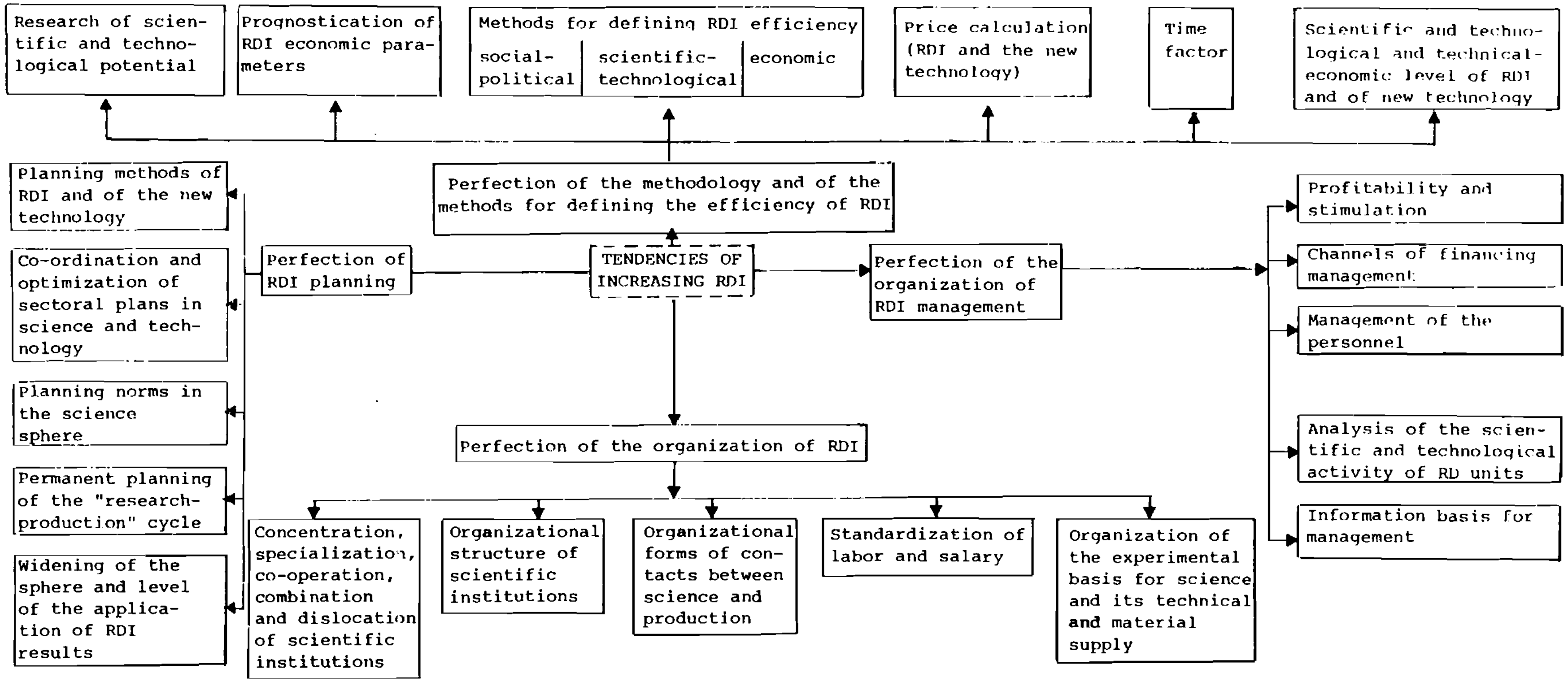


Table 3. System of RDI management.

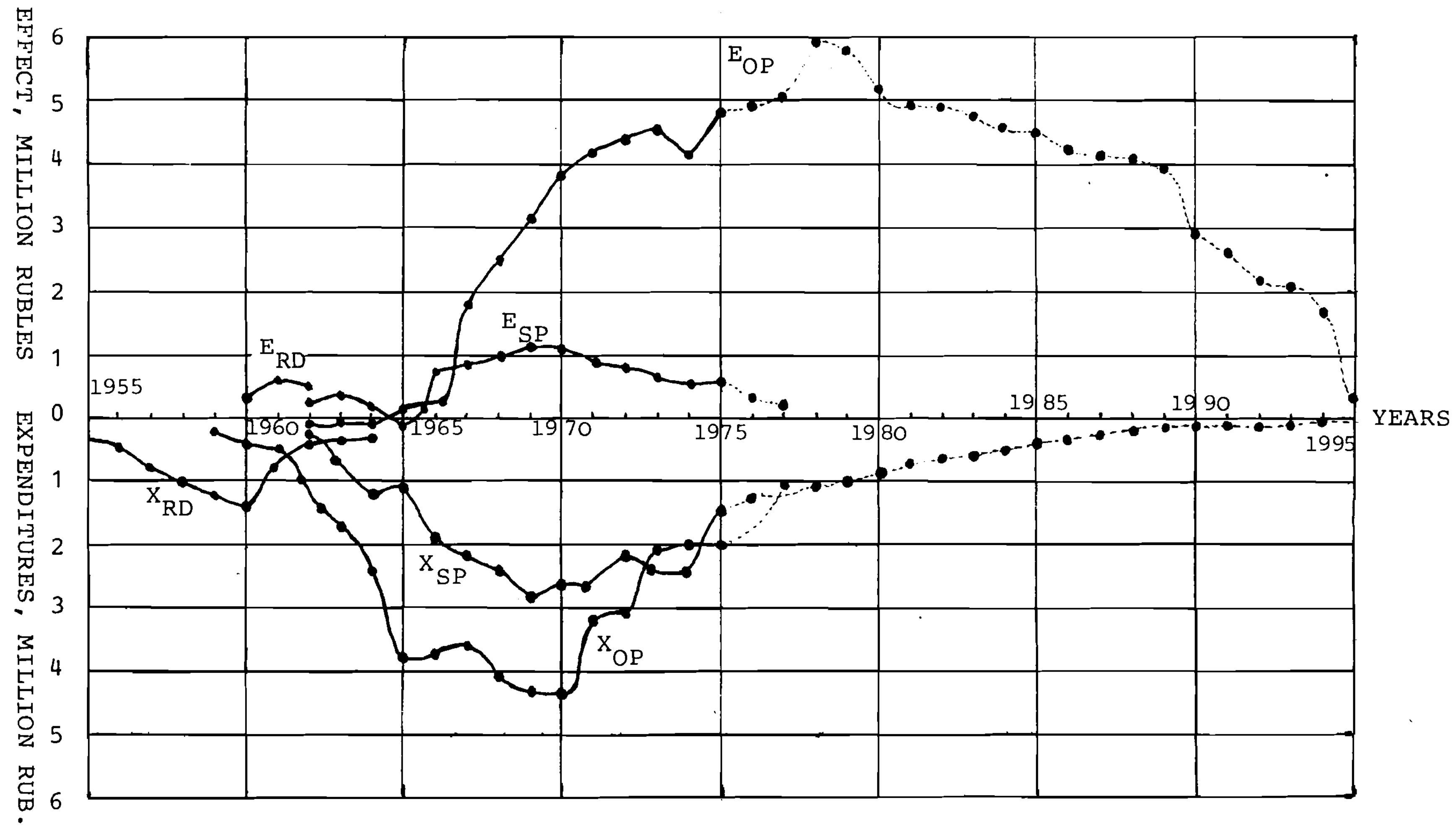


Figure 4. Relationship between effect and expenditures, according to the stages of the life cycle.

(X_{RD}, X_{SP}, and X_{OP} = expenditures on R & D, serial production, and operation respectively; E_{RD}, E_{SP}, and E_{OP} are the corresponding economic effects)

$$E_i = \frac{100W_iK_i}{\sum_{i=1}^{n} W_iK_i}$$

where

E_i is the share of economic effect ascribed to sector i;

W_i is the volume of wages spent on this project in sector i;

K_i is the coefficient of creativity of the i-th sector; and

n is the number of spheres (in our case $n = 3$).

The result of applying this formula to the given case are shown in Table 4.

R & D Modeling for Budgetary Decisions

During 1975-78, Project ERAND (Energy Research ANd Development, conducted at the University of Michigan) was conducted to develop and explore the applicability of quantitative energy R & D planning tools which would overcome some of the following limitations of quantitative models for R & D decision making (Baker and Freeland 1975).

1. inadequate treatment of risk uncertainty,
2. inadequate treatment of multiple objectives,
3. inadequate treatment of project interrelationships,
4. no explicit incorporation of the experience and knowledge of the R & D manager,
5. inadequate treatment of nonmonetary aspects of R & D,
6. models perceived by the R & D managers as difficult to understand and use,
7. inadequate treatment of the time-variant property of data and criteria.

The basic approach used in ERAND was that of multiobjective decision analysis (Keeney and Raiffa 1976). On the basis of a review of U.S. government documents, the multiple objectives of energy R & D may be condensed into six general areas:

1. economics (cost per unit energy output);
2. timeliness (how soon the process will become available for commercial use and how well the new process fits into the energy-economic context of that future time);

Table 4. Results of distributing economic effect among spheres involved in transportation technology case.

Sphere	Distribution of effect, %	
	In fact, according to place of receipt	Accounting for relative participation
R & D	1.1	29.0
Serial production	7.7	24.0
Operation	91.2	47.0
Total	100.0	100.0

3. environmental, safety, and health characteristics (to the extent that these social costs are not internalized in the economic costs of the process);

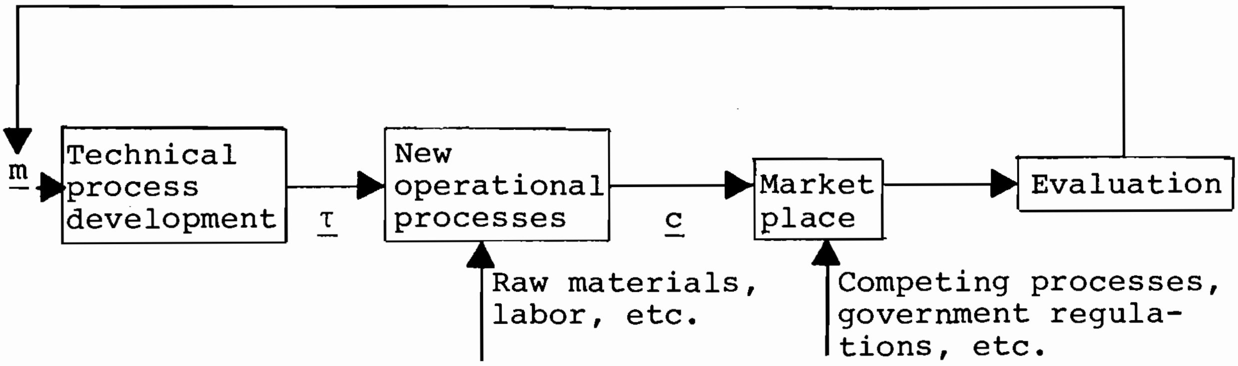
4. basic research (those contributions of the R & D program that have applications beyond the particular new energy process under development);

5. institutional factors (public image considerations and government-industry interactions (interference and cooperation));

6. national security (primarily the decrease in dependence on foreign energy sources made possible by the new process).

Project ERAND was divided into two stages of investigation: (1) intra-fuel budgetary decisions and (2) inter-fuel budgetary decisions. A top-down approach was taken to focus on the budgetary tradeoffs among programs at the top for intra-fuel budgetary decisions. This approach was applied, as an example, to the coal liquefaction programs within the coal (intra-fuel) area (Chen et al., 1977). The logic was based on the schematic diagram in Figure 5., which also contains a legend of the symbols in the following equations.

A significant characteristic of R & D is its uncertainty. At a given level of funding, the cost per unit energy output and the time of commercial availability for a given future energy process is uncertain. To carry out the decision analysis for budgetary allocation among several projects, it is necessary to obtain the probability density function $f(c,\tau|m)$ over new process product costs c and development times τ, given funding levels m. Technical factors common to more than one project will introduce correlations between outcomes of those projects. This interdependence is especially important in intra-fuel programs and can be modeled by defining $R_1, R_2, \ldots, R_q$ different common technical



$\underline{m}$ = amounts of money budgeted to various research programs

$\underline{\tau}$ = times at which new processes are operational

$\underline{c}$ = product costs of new processes.

Figure 5.

elements, with r_i a specific outcome of research on R_i. Then the probability density function for N different R & D projects can be written:

$$f(c,\tau|m) = \sum_r f_r(r|m) \prod_{k=1}^{N} f_i(c_k,\tau_k|m_k,r)$$

Two simplifying assumptions can be made for U.S. coal energy R & D programs at substantial funding levels. First, since these programs are relatively close to commercial use, the cost per unit energy output may be dictated more by the chemistry of the process than by funding level. Secondly, for a given value of r, τ_k may be approximately independent of c_k. Thus

$$f(c,\tau|m) = \sum_r f_r(r|m) \prod_{k=1}^{N} [f_k^{\tau}(\tau_k|m_k,r)f_k^{c}(c_k|r)] \quad .$$

There is also uncertainty in the market in which a new process will compete, and there are uncertainties in the new process meeting the various R & D objectives listed previously. If we restrict our attention on R & D objectives to discounted cost savings, the market situation is best described by competing cost function $c_o(t)$, the product cost per unit energy at time t using energy processes available without R & D funding. Then the measure of benefit for the new process, the expected discounted cost savings, would be:

$$\bar{U} = \int_{\tau_1} \int_{c_1} \int_{t=0}^{\infty} S(t|c_1,\tau_1,c_0(\cdot))[c_0(t) - c_1] \cdot e^{-\alpha t} dt f(c_1,\tau_1) dc_1 d\tau_1$$

where $S(t|\cdot)$ is the share of the market captured by the new process at time t. When R & D fund allocation between two new processes in the same market is considered, the expected discounted cost savings of the two processes must be considered jointly, since the benefits of each depend upon the product cost and development time of the other. The expected discounted cost savings is then

$$\bar{U} = \int_{c_1} \int_{\tau_1} \int_{c_2} \int_{\tau_2} U(c_1,\tau_1,c_2,\tau_2) \cdot f(c_1,\tau_1,c_2,\tau_2) d\tau_2 dc_2 dc_1$$

where

$$U(c_1,\tau_1,c_2,\tau_2) = \int_{t=0}^{\infty} \{[s_1(t) + s_2(t)]c_0(t) - s_1(t)c_1 - s_2(t)c_2\}e^{-\alpha t}\, dt$$

The share functions $s_i(t)$ are each specified by all product costs and development times: c, τ, and $c_0(.)$. In the following we will assume that after a process is developed $(t > \tau_i)$, its share increases by a fixed fraction of the market each year that it is the cheapest process on the market. The share held by a process decreases by the same fixed fraction each year that it is the most expensive process on the market. Otherwise, the share remains unchanged.

The above model has been applied to the budgetary consideration for two promising coal liquefaction technologies based on direct hydrogenation: H-Coal and Synthoil. Both processes depend upon coal gasification as a hydrogen source and thus have some common technical elements. Both processes compete to some degree in the same market. The decision problem to be analyzed in this example is the choice of one of two budgetary alternatives: a) Go H-Coal - most of the funds are spent on a new H-Coal pilot plant and b) Go Synthoil - most of the funds go to a new Synthoil pilot plant.

Based on the data and probabilities elicited from knowledgeable experts (Chen, et al 1977), computer runs were made, using the previously given equations. The results are shown in Figure 6, a plot of $\bar{U}$ as a function of mode product cost of Synthoil. It is interesting to note that the Go Synthoil strategy was found superior even at model Synthoil costs well *above* the model H-Coal cost. It shows that the intuitive decision *rule* of favoring the program with lower expected energy cost and lower uncertainty is not reliable. Where the new technologies being considered are apt to be relatively expensive compared with the existing technology, it may be wise to favor the R & D on the more uncertain technology since its cost probability mass that is below the competing cost may be greater than that of the more certain and less costly (on an expected basis) new technology. Only a quantitative model for R & D budgetary decision can make this kind of comparison accurately and reliably (assuming, of course, that the data obtained from the experts are credible).

As we moved into the second stage of Project ERAND, we focused our attention on inter-fuel budgetary planning and decisions; i.e., allocation of R & D funds among coal, nuclear, solar, conservation, etc. In the context of multiobjective decision analysis, the following characteristics distinguish inter-fuel R & D budgetary decisions in comparison with intra-fuel decisions (Chen, et al 1978)

1. there is more importance, and more disagreement, associated with the non-economic criteria,

2. there is significant disparity in uncertainty assessments,

3. the decision process is more political.

Strictly from the standpoint of rational analysis, there were no conceptual and technical difficulties in extending the quantitative approach explained and exemplified above for intra-fuel budgetary decisions to inter-fuel decisions. In practice, however, one is faced with the issue of synthesizing real decision process understanding with rational analysis. Several stances may be taken in this respect.

At one end of the spectrum is making all analyses subservient to the play of power (Wildavsky 1964) among the proponents of maximum budgets for the various fuel areas. This stance most resembles the current practice in the U.S. By taking this stance, the budget proponent in a particular fuel area would use analyses *internally* to check his intuition (like the example given previously). *Externally*, the budget proponent would use his analyses to back up *his budget* request and to counter his opponents. In this mode, the analysis results are to be used externally and thus restricted mainly to economic and tangible aspects (e.g., the amount of sulfur dioxide emission expected from a new process, or the cost of removing the emission, but *not* the tradeoff between economic savings and environmental protection). This kind of analysis does not make decisions. It is only a part of the decision process, and must be augmented and complemented by implicit and qualitative process considerations.

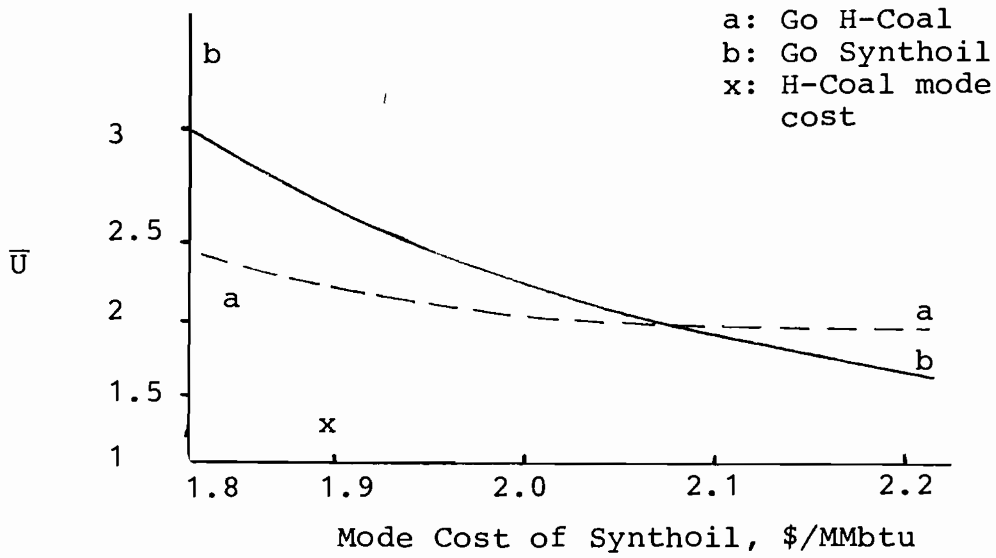


Figure 6.

At the other end of the spectrum is taking all process aspects into account by comprehensive decision analysis. To be useful, such analyses would be performed for or by a specific decisionmaker who would combine in the rational analyses all factors which are relevant to his decision. This is an antithesis of the first stance described above. By taking this second stance, the decision analysis would take into account not only the non-economic and non-tangible criteria in all the six objective areas listed previously, but also all the organizational, political, and personal considerations, as long as they impinge upon the budgetary decisions which the decisionmaker is empowered to make. For example, the program manager of each fuel area would include the probability of his budget "salability" in his decision on the budget level to propose. The assistant secretary for energy research would include in his utility function the maintenance of basic research capability, the acceptability of the proposed budgets to the various Congressional committees, as well as the contribution of the proposed programs to the national energy plan. Although this approach appears quite straightforward to decision analysts, we do not know of any actual analysis of this type which has been used for real budgetary decisions. This is not surprising as exposed values or value tradeoffs are a political liability to public officials, let alone the wide range of political and personal considerations that must often enter a real decision (Kingdon 1973). Any practical difficulty is the ephemeral nature of the political situations. New compromises, pressures, quid pro quos, as well as new information, surface constantly so that there is very little time for formal decision analysis. The decisionmaker is forced then to resort to his experience, intuition, and judgment.

Two other stances may be worth mentioning briefly. One stance is due to Allison (1971) who proposed that the essence of a decision in the public arena can be captured only by examining it through multiple sets of conceptual lenses: the unitary rational actor; organization process; and governmental politics. Another stance is that of Value-Oriented Social Decision Analysis (VOSDA), which was proposed by K. Chen some years ago (1970) and is currently being tested in the real decisionmaking environment (K. Chen and J.C. Mathes, "Value-Oriented Social Decision Analysis", proposal to National Science Foundation, project established January 1978). The VOSDA approach is aimed at the possible use of decision analysis, not as a tool for decisionmaking, but as a means of facilitating the understanding of where and how different parties at interest (fuel area managers and their supporters) differ from one another, thus enhancing the chance of effective communications and conflict resolution among the parties at interest. It would also help public understanding and public participation in inter-fuel budgetary decisions. To the extent that neither process nor analysis completely dominates in Allison's approach or Chen's approach, they may be considered to occupy the middle ground between the two ends of the spectrum. To the extent that results from taking these two stances may lead to public understanding and participation in inter-fuel budgetary decisions, they may be considered to transcend the first two stances discussed in the last two paragraphs.

A Macromodel Relating RDI to National Growth

In the formation of long-range and five-year plans for RDI and also in the process of current management of the implementation of these plans, problems are constantly arising in regard to the balancing (coordination) of RDI policy decisions with the aggregated indicators of social and economic progress--in the name of which RDI activity is carried out. In connection with this, a task was posed for working out a model which reflects the interconnection of such variables as the following:

-- National income, m, in percent relative to a base year, or M, in absolute figures (milliards of rubles). Here X indicates the statistically evaluated rate of annual growth of M.

-- An economic estimate, l, of the growth in ST potential (that is, the annual appropriations for ST activity) in percent relative to a base year, or L, in absolute figures (milliards of rubles). Here Y represents the statistically estimated rate of annual growth of L.

-- An indicator of the intensity of the process of transforming "input signals" in the system (i.e., the growth of ST potential) into final socio-economic effects. As such an indicator, "τ" was chosen--the delay (in years) between the appropriations and the outputs into national income.

-- The time horizon of projected decisions--the time variable t (in years).

In the development of the model (Klimenjuk 1974, Brusilovski 1975), several basic ideas were used from econometrics and from the methodology of systems-management models with delay parameters. Also, a qualitative and quantitative analysis was made of existing statistics on ST advance. The mathematical description of the model was obtained on the basis of the hypothesis that the most important *measure of the effectiveness* of the systems under examination is, in the final analysis, reduction in *the necessary time* of economic reproduction. The model turned out to be similar to a single-sector Harrod-Domar model with delayed return on investment without discounting (Tinbergen and Bos 1962):

$$M_{(t+1)} - M_{(t)} \cong \frac{dM}{dt} = \eta(t,\theta)\ L(t - 0) \quad ;$$

where $\eta(t,\theta)$ is a proportionality factor, a so-called "norm" for return on investment, and θ is the interval of real time needed for this return to be obtained.

$\theta = \theta_1 + \theta_2 + \theta_3$, where θ_1 is the delay in return on investment caused by the mean duration of R & D; θ_2 is the same, caused by the time required in the given national mechanism for technology transfer; and θ_3 is the same, caused by the level of intensity, characteristic for the given country, of the productive utilization of technological innovations.

The basic organization-management possibilities for accelerating national income reproduction through factors of technological progress were investigated and statistically evaluated. In particular, sets of absolute quantities τ (that is, the time required for realization of the applied potential of technological results) were obtained for various countries and various periods of development (Brusilovski 1975).

Using statistics for the USSR in the years 1961-1970, an estimate of $\tau \cong 9$ years was obtained. This coincides well with data obtained by other authors using different methods. Also well-known is the series of publications on the statistical analysis and evaluation of technological progress begun by the pioneering work of E. Mansfield (Mansfield 1961). In these publications, similar estimates of "lag" are repeatedly encountered, based on historical and statistical data relative to the experience of various technically developed countries. Typical estimates of τ range from 6 to 14 years.

The model developed here has been implemented in the form of computer programs. For convenience in preliminary approximate calaculation, we can also use special nomograms which graphically illustrate the character of the internal dependencies among variables. In Figure 7 is represented a nomogram of this type, which was prepared for use in prognostic calculations and the balancing

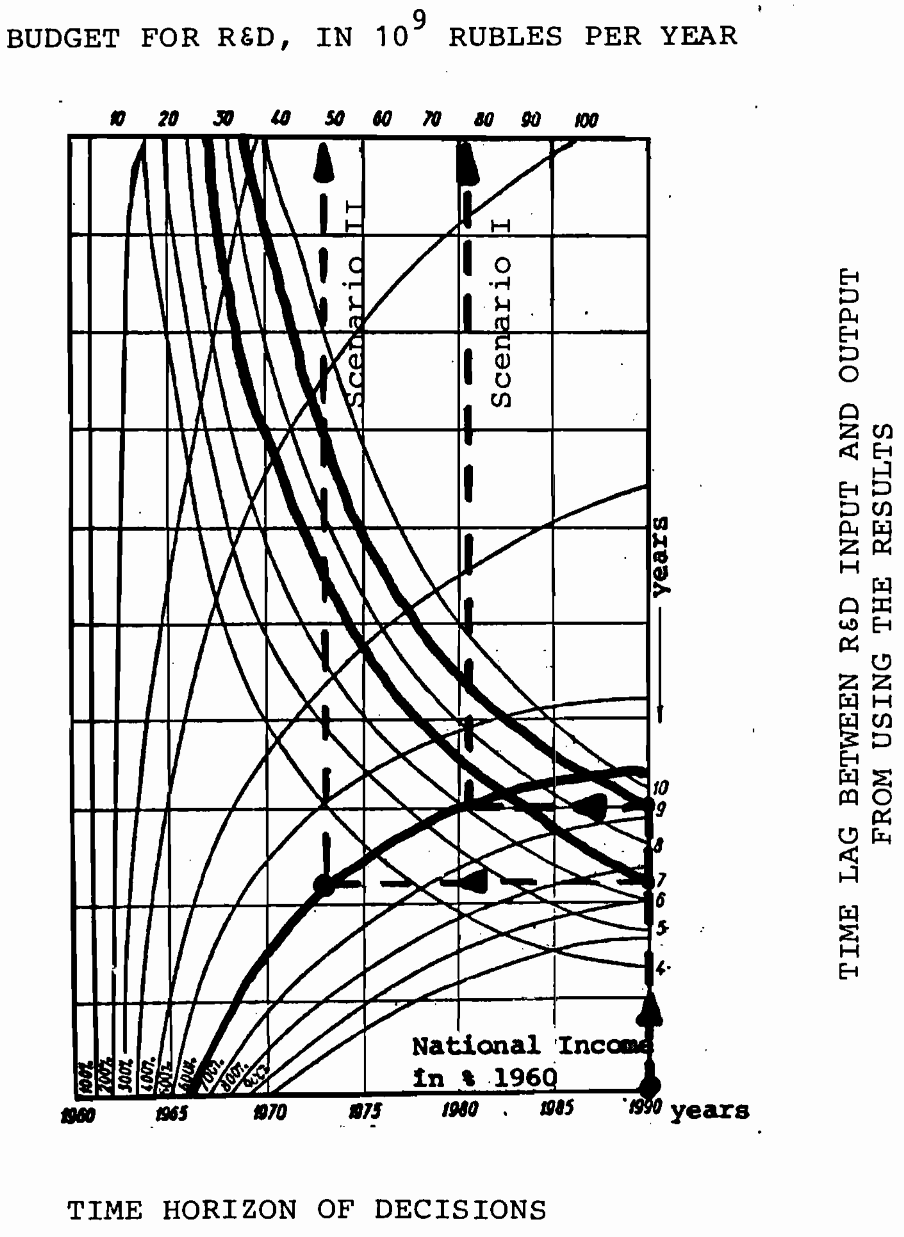


Figure 7. A macro model for science and technology policy in the USSR.

of variants of planning decisions in the USSR. Use of this nomogram is demonstrated in Table 5, which shows two variants of possible policies. This pattern is an illustration of the great potential of socio-organizational arrangements of technological change.

Four classes of urgent practical problems have been discussed with the help of these models.

1. To substantiate an hypothesis about the needed level of funding for ST activity, when there is an intention to set a definite task for raising the level of national income (t, m, τ are given, and L is to be estimated).

2. To substantiate a prognostic supposition about the statistically expected increase in the level of national income, given imposed limitations on the budget for ST work and the already established level of intensity of the cycle of obtaining and implementing technological results (L, t, and τ are given, and m is to be estimated).

3. To prepare data for drafting variants of plans about the possible time-spans needed to achieve certain socio-economic goals, given the statistically expected contribution to solution of this problem which will be made by technological progress with its characteristic level of intensity in the engendering and transmission of new technology (m, L, and τ are given and t is to be determined).

4. To investigate how strenuously tasks for perfecting the organizational and economic mechanism for technology transfer and for acceleration of the whole cycle of ST work must be posed, if supposition about final economic goals and limitations on budgetary structure are already known (m, t, and L are given, and τ must be determined).

Table 5.

	Time Horizon	National Income Growth	Time-lag T, (years)	Final annual level of necessary R & D budget
Scenario I	1960-90	700%	9	76.10^9
Scenario II	1960-90	700%	7	48.10^9

In this report we need not present further details of the model. In conclusion, however, it is appropriate to give some attention to one peculiarity of this model, namely its orientation toward the generation of systematically substantiated answers to questions of the "what if" type. We are convinced that this approach is extremely valuable in any model which is used for policy planning.

This feature of the model is used in order to formulate clearly and assess critically the systems assumptions (the "if" conditions) corresponding to various alternative forecasts obtained by different methods. It often turns out that these assessments have not been taken into account.

Thus, for instance, the investigator may find an attractive hypothesis $M(t_i)$ developed with a certain projected level of $L(t_i)$. The analysis can show that these two estimates for the time t_i are probable and mutually compatible only if there is an unprecedently high level of intensity in the cycle of ST work and technology transfer (e.g., $\tau \leq 4$ years). Balancing of the system of hypotheses, reducing them to the level of the critical estimate (on the order of $\tau \cong 6$-7 years), makes the whole problem if not simple at least realistic.

Such an analysis, performed on the data of various countries, has also made it possible to identify "statistically significant" methods for intensifying the cycle of technological work and technology transfer--that is, methods which have a substantial influence on the final macro-indicators. Among them we can single out (for national RDI policy) the rational structuring of the set of "candidate technologies" by scale of utilization, rate and sequence of transfer, etc. (Candidate technologies are R & D findings, the possibility of introduction of which (from the physical, chemical, engineering, and other viewpoints) is not doubted by the majority of the specialists.) We are talking here about the need for more profound substantiation of the "national assortment" of technological systems currently being developed.

For the international scale of ST policy, it is important to indicate that international exchange of new technology (in its various known forms) allows all countries to improve the structure of ST efforts. A significant part of their investments for ST can be diverted into projects having a naturally short cycle of realization. Thus they can intensify the process of technology transfer within the country and raise the effectiveness of technological progress. Both sets of measures must be examined, within the RDI policy design, as mutually complementary and connected elements.

A Model for Planning RDI Activities

In constructing a model to aid management of a specific RDI project, system analysts are faced with the task of reflecting in the model the problem's cause-and-effect connections and a certain part of its engineering logic. At the same time, the model must also contain other data necessary for decision making relative to organizational management. One type of model suitable for these purposes is the network type known in Soviet parlance as SPU ("setevoe planirovanie i upravlenie", network planning and management). We shall describe the SPU approach on the basis of a case study in the area of the science, technology and exploitation of computers (Dobrov 1972; Glushkov 1969; Dobrov et al 1974).

We set ourselves the task of reflecting in the model the ideas of specialists, quantitative assessments of events and possibilities, and also the qualitative peculiarities of the logic of the development of the chosen ST area. Assessed in the framework of SANT, "technological changes" in the model are related to four levels of scientific and engineering activity:

a. to the sphere of basic or exploratory research, the forming of the "portfolio" of new ideas for further development;

b. to the sphere of applied research and development directed toward discovery of methods for practical use in technology of the already projected possibilities and established principles;

c. to the sphere which seeks economically and technologically effective methods for realization of the results of work at levels (a) and (b) in conditions of real production;

d. to the sphere of technology transfer and the utilization of "technological changes" in regular practice.

The essence of the methodology consists of informational and mathematical procedures for construction and analysis of a basic graph which reflects the generalized perception of a large group of specialists about needs, possibilities, and resources for technological changes in a definite area of R & D (Figure 8).

The organizers of this type of SANT use a goal-oriented and multistage expert inquiry in striving to clarify and formulate the set of expected and needed events. (In working with experts, we take account of positive experience in the development and application of the Delphi method. At the same time we have tried to avoid a number of traditional weaknesses of this method. The procedure which we have constructed for permanently conducted expert estimations is an example of the "non-conventional Delphi", see Linstone and Turoff (1975) and Sackman (1975).) These events reflect the conditions for achievement of each level of progress in the area. Each such event is accompanied by a system of quantitative estimates (t_j--the expected time of occurrence of event j; $P_{ij}(t)$--the relative probability of the transition of events from condition i to condition j in time t; C_{ij}--an estimate of the cost of realizing the indicated elementary step of technological progress; Z_{ij}--the relative importance of the i-th event as one of the conditions for occurrence of event j). The structure of the graph reflects a logical network of cause-effect

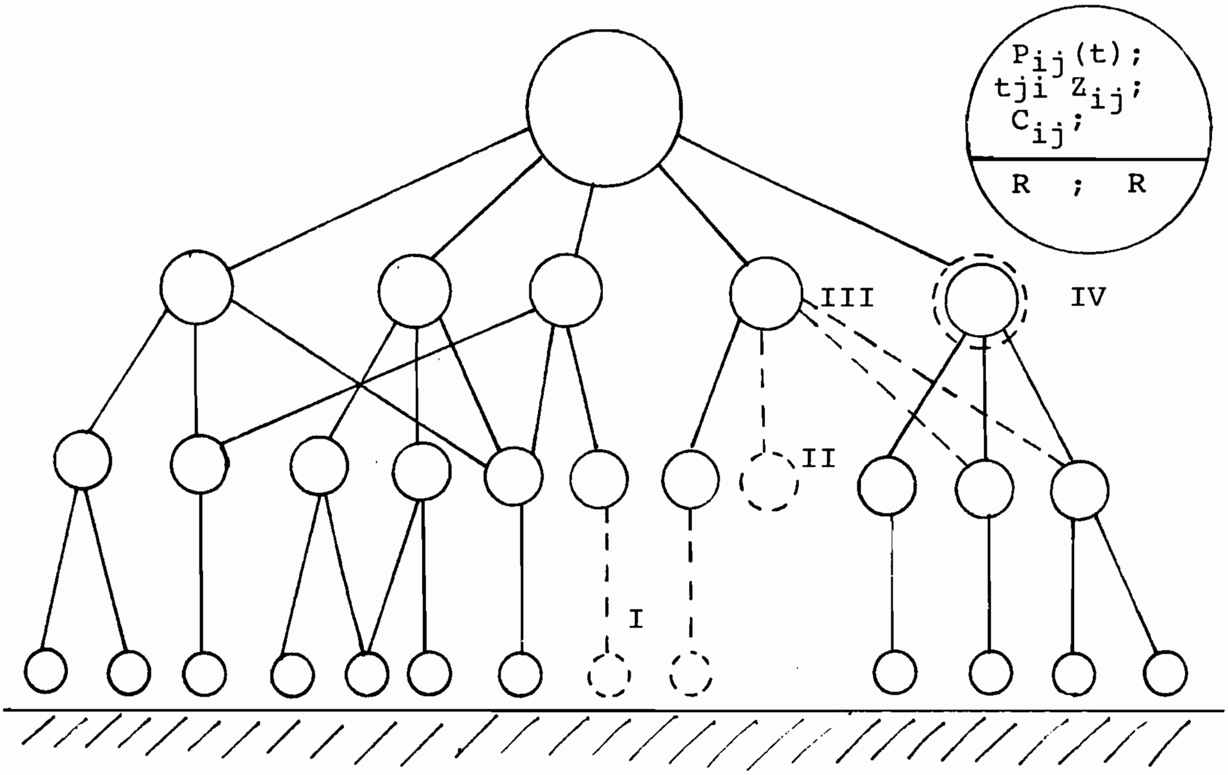


Figure 8. Model of technological change.

relations among the set of events included in the graph. The sequence followed in constructing the graph amounts to "extending" some problem (the final goal of the R & D program) from the future down into the present, creating a structure of intermediate events, and fixing cause-effect relations among them.

"Technological changes" per se are modeled by means of a combination of several formal transformations of the graph (see Figure 8):

I introduction (or removal) of events which reflect possibilities for achievement of previously established goals;

II introduction of new formulations of conditions or description of new sub-goals;

III reconstruction of the network of connections among the events (establishment of new ones or liquidation of existing ones);

IV changes in the set of quantitative characteristics of the events in the graph. (An important element in the information included in this system of knowledge is data about specialists and organizations which are ready to perform different tasks or are relevant to such a type of planning activity.)

The methodology based on these ideas has received the name "Programmatic Methodology for Technological Forecasting". In 1971 it was approved by the collegium of the State Committee on Science and Technology of the USSR as the basic methodological instrument for SANT. Since 1975, the CMEA countries have had a Joint Methodology for Multinational Work in Technological Forecasting created on the basis of the "Programmatic Methodology" but utilizing the CMEA countries' experience with forecasting.

With the use of these methodologies, and in various technological areas, assessments are now being obtained which are practically related to all the elements of SANT: prognostic technological data; estimates of the possible influence of technological data; estimates of the possible influence of technical achievements; comparison of variants of technological policy; comparison and evaluation of R & D projects at the stage of their inclusion in plans and programs; and advance estimation of the ST potential which could be drawn in form performance of expedient efforts.

The practice of working with the model can be characterized in the following way (Glushkov 1969). A representative sample of experts, often numbering in the hundreds (with variable membership in each round of the inquiry), puts forward technological conditions for the achievement of a certain level of goals and subgoals. The procedure of expert estimation continues until it reaches such conditions as the use of already extant R & D results, the implementation of an already patented solution, the introduction of an innovation which can be brought on license, etc. This operation is known as "grounding" the graph.

The networks of hypotheses which are constructed in this way include thousands of events and serve to systematize a great deal of information about technological ideas and possibilities. Such a formalized presentation of the generalized opinion of specialists possesses a number of interesting and non-trivial properties.

First of all, the graph contains important information which no one specialist by himself posesses--not even the most highly qualified and erudite. This information is subject to structural analysis and calculations through the application of quantitative methods.

A program has been developed and implemented on the computer which allows us to determine the optimal path for achievement of the final goal (optimal in terms of time, cost, etc.), and also the importance of various events and chains of events (variants) for solution of the initial problem. In addition, we can quantitatively evaluate such properties for technological policy alternatives. The computer also performs some rather cumbersome operations for putting the information in the graph into good order, such as liquidating "dead ends" and loops, and other operations necessary for the subsequent analysis and calculations.

Computations are carried out according to the formula:

$$q_{t_k}(j) = \sum q_{t_o}(i) P_{ij}(t) \quad ,$$

where $q_{t_k}(j)$ is the absolute probability that time t_k the system will be in condition j;

$q_{t_o}(i)$ is the absolute probability that at time t_o the system will be in condition i;

$P_{ij}(t)$ is the relative probability that the system being forecasted will, by time t, move from condition i to condition j $(i,j = 0,1,\ldots,N;$ $K = 0,1,\ldots,n)$.

Conditional estimates of the probability of achievement of the subgoal S_i by the time t are calculated as proposed by V. Glushkov.[1]

$$P_i(t) = \frac{1}{R_i} \sum_{E=1}^{E=l} R_{iE} \cdot P_{iE}(t - t_{iE}) \cdot P_{iE1}(t - t_{iE}) \cdot$$

$$\cdot P_{iE2}(t - t_{iE}) \ldots P_{iEN}(t - t_{ie}) \quad ;$$

where P_{iE} is the probability of achievement of subgoal i estimated by expert number E;

l is the total number of experts in the group;

$P_{iE1}, P_{iE2} \ldots P_{iEN}$ are the probabilities of accomplishment of a chain of intermediate events (1,2,...N) suggested by expert E as conditions for achievement of the subgoal i;

R_{iE} is the weight co-efficient for weighting an estimation made by the expert E about subgoal i;

R_i is the general weight coefficient of the expert group.

There are also other computational formulas and algorithms for different specific compositions of data and different functions of SANT. They make it possible to perform a qualitative analysis of the chains of interconnected events from a common viewpoint and to carry out quantitative computations of their characteristics with compatible estimates. This analysis embraces data about goals and subgoals, paths to their achievement, the resources required for this, and the existing ST potential.

One of the most important properties of the model examined here is the possibility of working with the graph with the help of a new type of dialogue--a dialogue between "man, information system, and the community of specialists."

As a natural reflection of the logic of the process of technology creation, each event is connected not only with that nearest to it, but through that to the subsequent events. Thus the attainment of the final goals depends in various ways on the individual fates of the separate events. The graph allows the analysts to play out the situation and thus test a series of hypotheses of the type: what kind of consequences could be expected in the program from occurrence of event j in the period $\pm \Delta t$; or how does the absolute probability of achieving goal S change if the relative probability of transition from event i to event j turns out to equal zero (failure).

Owing to the specific character of technological change as an object of SANT, at any given moment there are a certain number of events in the graph for the realization of which none of the experts could suggest conditions. In the real course of performing ST work, possibilities for further development of the graph become clearer (both under the influence of world experience and on the basis of one's own R & D). These possibilities reveal the ways of completing ("grounding") those branches which could not previously be grounded. At the same time, ideas about structural connections and previously suggested quantiative estimates for other events are made more exact.

Under the influence of information newly entered into the system, periodic revision is performed on the previously made estimates, forecast variants, and decisions. The results of such an analysis can give the system "reason" for re-examining one or another part of the plan of practical actions and for discussing the newly formed situation on an informal level.

In every case, a valuable managerial possibility is the fact the agency responsible for decision making can know the "cost of error" or the "cost of non-optimality" in decisions taken under the pressure of external circumstances.

Use of the model's indicated capability for "self-improvement" and "self-instruction" opens up especially favorable prospects for formation of a new methodology for the planning and management of ST changes. Its basic features are as follows:

-- providing a single set of decisions, embracing research work on various levels, development work, and the technical improvement of production;

-- making key management decisions under conditions of fuller knowledge and with the use of calculated analytic bases;

-- carrying out planning as a permanent procedure, i.e., at any moment of the 15 year plan it will be possible to update current decisions in light of the long-range perspective;

- -- obtaining a single methodological substantiation for the choice of goals, for assessment of dynamics of technological change, for long-range program design, and for the distribution of resources;
- -- making it possible for a broad circle of specialists (people having concrete ideas and suggestions) to introduce their information into the bank of data used in SANT. The input of such data can change the previous estimates and can influence both the SANT and the decisions being made. We would emphasize that the most important influence which such new ideas exert in the model is not through statistically averaged numbers but through change in the set of events and the structure of their interconnections. Attention to individual judgments has a stimulating influence on the activeness of this process of "competition of ideas".

A Model of R & D Project Dynamics*

In this section we shall describe a simulation model of the dynamic behavior of a research and development project, in which progress toward project completion (and thus the project's ultimate consumption of time and effort) is related to various motivatonal and managerial variables.

The model to be presented (see Figure 9) consists of thirty equations, plus associated initial conditions and constants. The format of level and rate equations is that used in the Industrial Dynamics methodology of Forrester and his associates (Forrester 1961)(now called System Dynamics), and the equations presented in the manner called for by the DYNAMO compiler-simulator (Puch 1973).

The initial equations are those for the real progress rate and the level of cumulative real progress. The progress rate is represented as the product of the average level of manpower recently at work on the project and their average productivity in job units per man per month. This rate of real progress integrates continuously to form the cumulative progress.

$$PR.KL = (AMEN.K)(PROD.K)$$

$$CRP.K = CRP.J + (DT)(PR.JK)$$

$$CRP = 0$$

PR = Progress Rate (job units/month)

AMEN = Average MEN on project (men)

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*This description is a shortened version of a paper by L.B. Roberts of the Alfred P. Sloan School of Management, M.I.T. (1974)

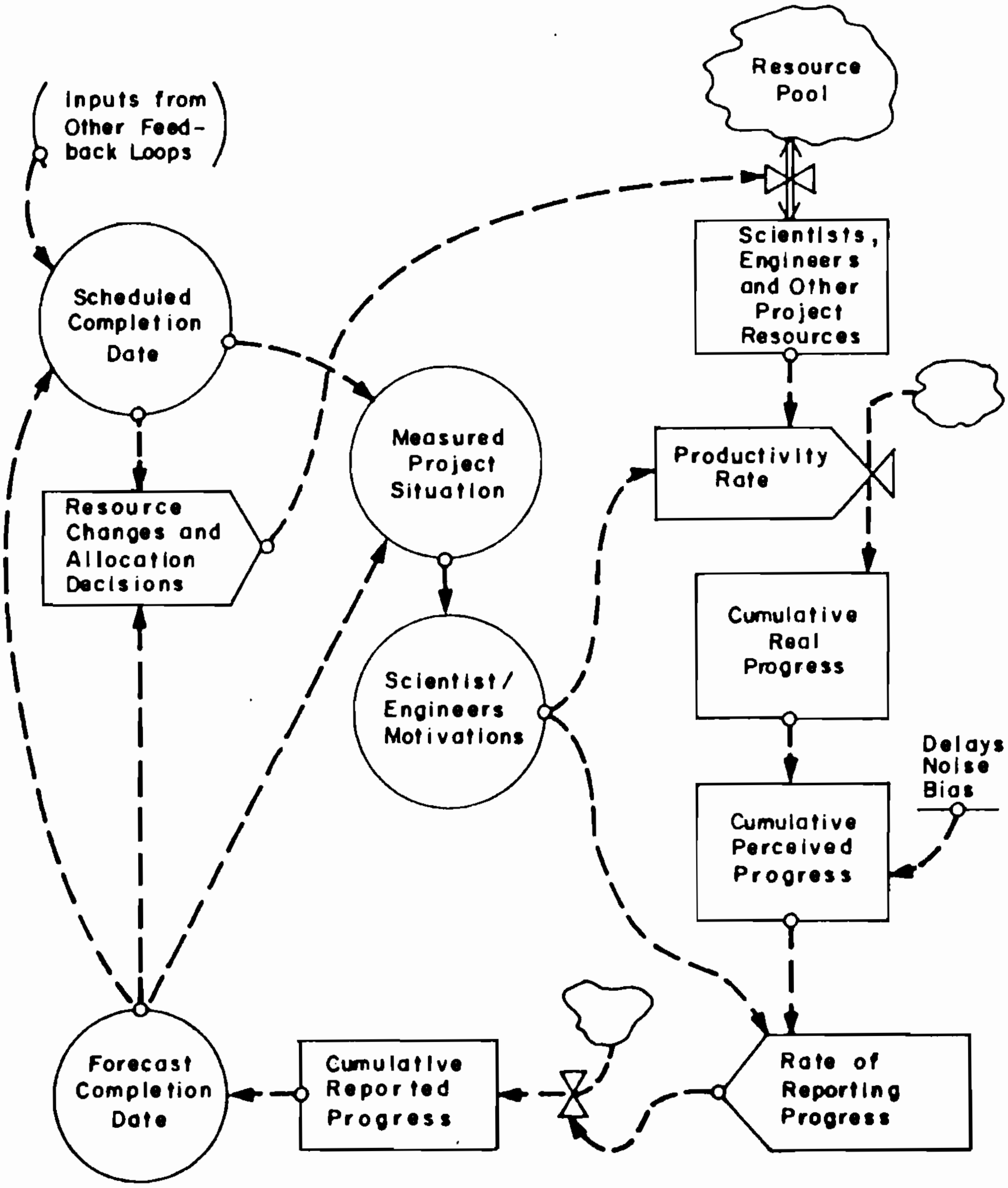

Figure 9. R & D control system.

PROD = PRODuctivity (job units/man-month)

CRP = Cumulative Real Progress (job units)

DT = Delta Time, DYNAMO time interval between computer calculations (months)

K and I = indexes of "present" and "previous" steps in modeling process.

However, the real progress is not the basis of action in the project, except as it is perceived. Anyone who has worked in R & D knows that there may be a significant difference between the real achievement and the perceived progress on a job. We thus now formulate a level of perceived progress which sums the perceived progress rate as well as perceived errors in earlier progress perceptions.

$$\mathrm{PCP.K} = \mathrm{PCP.J} + (\mathrm{DT})(\mathrm{PPR.JK} + \mathrm{PECR.JK})$$

$$\mathrm{PCP} = 0$$

PCP = Perceived Cumulative Progress (job units)

PPT = Perceived Progress Rate (job units/month)

PECR = Perceived Error Correction Rate (job units/ month).

The current progress rate that is perceived is the product of the manpower currently employed on the project and their perceived average productivity.

$$\mathrm{PPR.KL} = (\mathrm{MEN.K})(\mathrm{PPROD.K})$$

PPR = Perceived Progress Rate (job units/month)

MEN = MEN on project (men)

PPROD = Perceived PRODuctivity (job units/man-month)

L = Index of next step in modeling process.

To the extent that the perceived progress rate differs from the real progress rate, an error in perceived cumulative progress will gradually accumulate. Here one of the important characteristics of research and development, the usual relative intangibility of the project progress, has its effect. The further the project is along, the greater the likelihood that product assembly and/or test will reveal errors in earlier progress estimates. We therefore model the organization's rate of correcting perception errors as being a fractional part of the error, where the fraction of the error that is perceived increases significantly as real project progress approaches job completion.

```
PECR.KL = (FER.K)(CRP.K - PCP.K)
FER.K   = TABLE(TFER,PJC.K,0,1,.2)
TFER    = 0/0/0/.5/.8/1
PJC.K   = CRP.K/ER
ER      = 1200
```

PECR = Perceived Error Correction Rate (job units/month)
FER = Fraction of Error Recognized (percent/month)
CRP = Cumulative Real Progress (job units)
PCP = Perceived Cumulative Progress (job units)
TABLE = DYNAMO special TABLE lookup function, for data tables
TFER = Table, Fraction of Error Recognized (percent/month)
PJC = Percent of Job Completed (percent)
ER = Effort Required (job units).

The fractional error perceived as a function of the cumulative real job progress is shown in Figure 10. Values for the curve are given by 6,C. Each job is represented by an effort requirement of a number of job units. For the initial model simulations, the job size has been designated as 1200 job units. At a productivity rate of two job units per man month, this job size indicates a requirement of 600 man-months of scientific/engineering effort.

The actual productivity of the average scientist/engineer working on the job is represented simply by his normal productivity and a multiplier that reflects motivational aspects. Give no particular pressures from scheduling considerations, scientist/engineers are usually self-motivated to turn out well-engineered products that incorporate additional reliability, desirable but not necessary features, perhaps more aesthetic appearance, etc. At an extreme such activities constitute unnecessary (sometimes dysfunctional) gold-plating. Thus with low schedule pressure some of the R & D work does not really contribute to principal project objectives, and only a fractional part of the technical effort is counted as being real progress on the job. Conversely, as pressure for more productivity gradually builds, the scientists and engineers respond relatively quickly by a greater concentration on the essential tasks. With greater pressure the technical effectiveness grows further, accelerated by the tendency of the engineers to put in longer hours at work. An excess of pressures stemming from a large forecast schedule slippage, however, tends to demoralize the R & D team and has effects of decreasing its productivity. These facets of motivational effects on technical productivity are pictured in the Productivity Multiplier curve, Figure 11.

This function was introduced into the model, as were the following other functions:

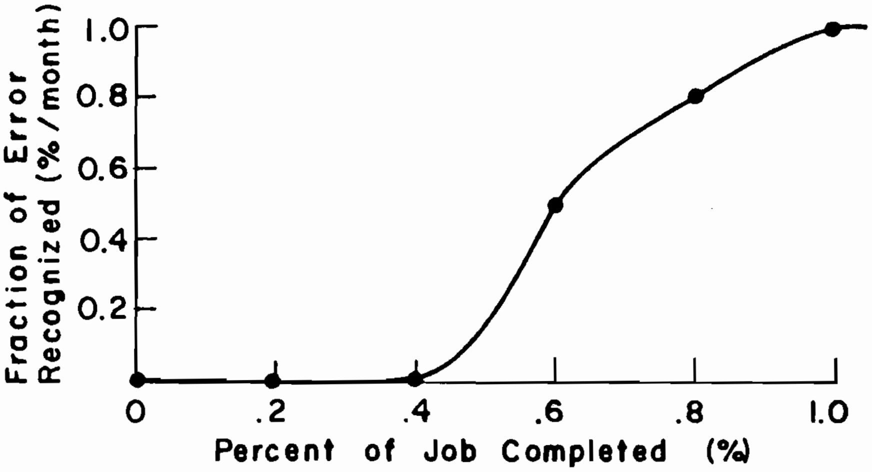

Figure 10. Tangibility effect on error detection.

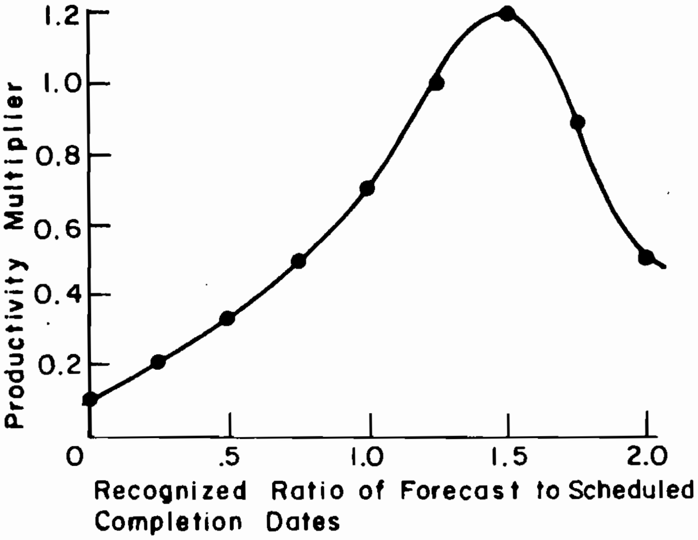

Figure 11. Motivational effects on productivity.

- -- Fractional Change in Manpower (percent/month) as a result of the Recognized Ratio of Forecast to Schedule Completion Dates;
- -- Fraction of Effort (percent) Remaining Reportable as Job Completed (percent);
- -- Fractional Change in Perceived Productivity (percent/month) as a function of the Recognized Ratio of Forecast to Scheduled Completion Dates.

Three additional variables were specified in model: the perceived percent of job completion; the reported percent of job completed; and the cumulative manpower effort on the project.

To be sure, the model developed thus far is only a first-order approximation of the complex system of research and development projects. Yet the system characteristics contained are sufficiently broad that they deserve study based upon DYNAMO simulation results.

Basic Model Behavior

Some of the key dynamic variables during the project life are shown in Figure 12. The project starts at time zero with a desired completion date of month 30. At a believed normal productivity of two job units per man-month, the project effort seems to require 600 man-months of R & D work. Spreading this effort evenly over the 30-month schedule demands 20 scientist/engineers on the project, the initial condition of the manpower level.

Under this initial condition of coincident scheduled and forecast completion time, however, group motivation is not particularly high, and the usual self-motivated goals of the scientist/engineers tend to produce over-engineering on the early tasks. The average effective productivity of the R & D staff--that is, their work contributing directly to project objectives--is therefore only 1.4 job units per man-month instead of the initally assumed two value. A basic problem source in research and development, however, is the relative intangibility of much of the work, particularly during the early phases of a project. Because of this intangibility, the perceived (and scheduled) progress, based on the two job units per man-month, cumulates at a faster rate than the actual progress (shown by the 'A' curve in the figure, beneath the Perceived Cumulative Progress curve). The gap is not detected until simulated month 17, from which date changes begin in the observable project behavior.

As the scientists and engineers and management sense the errors in their earlier perceptions of job progress, the cumulative progress flattens out with current progress rate estimates tending to just counterbalance corrections of earlier cumulative estimates. The forecast completion date for the

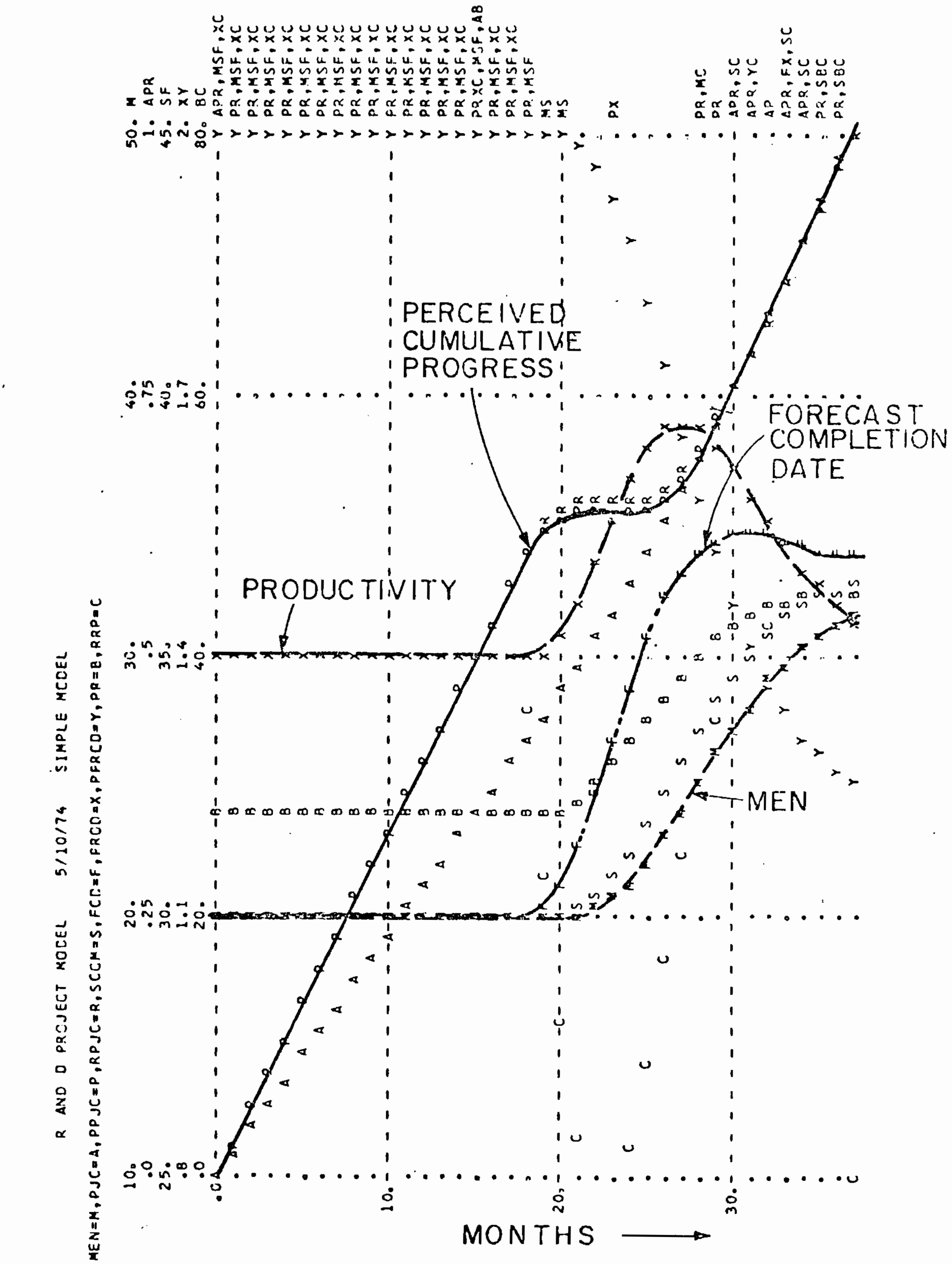

Figure 12. Basic model simulation.

project begins to climb, based on the new indications of work remaining and the assumed lower technical productivity, tapering eventually at month 37, a 7-month slippage from the original schedule. With this change in forecast, three observable changes also occur. First, under pressure because of the deviation of forecast completion from schedule, technical productivity begins to rise, peaking at 1.65 job units per man-month, an increase of about 20% above the earlier productivity. This productivity gradually drops back as the forecast and schedule come into line. The second change is that the company assigns more men to the project, going from its initial level of 20 men to 31 men by the end of the job. Finally, the schedule is slowly adjusted to take account of new forecast expectations, tending to reduce the pressure on the technical staff as it begins to become more aligned with the forecast.

These changes result in job completion during month 37, a 23% slippage of the original schedule. The total effort required is 822 man-months, in contrast to the 'ideal' case (i.e., steady productivity of two job units per man-month) of 600 man-months. However, the increased productivity that exists from about month 18 of the project does benefit the project. Had productivity remained at its initial 1.4 job units per man-month throughout the project, the cumulative effort required would be about 860 man-months. The productivity change thus produces approximately 5% savings of total effort (hence, total cost) in the project. It is interesting to note that productivity can thus be recognized as a dynamic buffer, decoupling manpower change from perceived job scope change, just as inventory can decouple production rate from sales rate.

Accurate Progress Perception

One of the important problems noted in the preceding discussion is that lack of tangible results causes delay until month 17 in the recognition of project problems. An interesting experiment, is a project simulation in which any error in perceived progress is immediately detected and corrected. (This was accomplished by changing the TFER table to: TFER = 1/1/1/1/1/1.) Under this assumption, perceived and actual progress remain together throughout the project. From the beginning of the project, this corrected perception causes changes in perceived technical productivity, which is soon reflected in the forecast completion date. The gap between forecast and schedule has some beneficial influences on productivity. However, the effect at no time is very great, and it soon diminishes toward its initial value. Cumulative required effort is 831 man-months, slightly more than in the basic model simulation, but other benefits do result from the accurate progress perception. The project is completed during month 35, five months behind initial schedule but two months ahead of the basic project. Furthermore, peak manpower is 28 scientist/engineers instead of the 31 of the basic run, thus indicating a small improvement in stability of the organization. These results, however, are not significantly different from the earlier base case. They imply that more tangible progress measures in research and development might not suffice to change the character of project management problems.

Immediate Schedule Adjustment

Policies for managing research and development projects can have significant impacts on results. The next three simulations describe various aspects of these policies as related to schedule and technical work-force changes. One was a policy in which schedules are immediately adjusted to correspond with changed forecasts of project completion time. (DCS was set equal to 0.5 months.) Such a practice may result from project funding of a 'level of effort' nature, in which only a certain number of men can be employed on the job. Alternatively, it may arise from lack of availability of additional scientist/engineers to assign to the project. In either case, as soon as detected problems result in a later forecast completion date, the schedule is adjusted to agree with the forecast. One effect that is obvious in the graph is that this situation generates little additional pressure or motivation to change the nature or rate of technical productivity. The organizational size is maintained at a stable level, rising only by one person during the project life. The brunt of the policy is seen to be schedule slippage, with the project reaching completion during the early part of month 42, a slippage of 40% of the original schedule. A penalty is also paid in a slightly higher total effort (cost) due to the lack of productivity gains during the project, with 853 man-months utilized on the job.

Fixed Schedule Policy

In contrast to the above case, Figure 13 presents the situation in which the initial schedule is treated as more or less fixed. (DCS was set equal to 96 months.) This kind of situation is true in 'crash' projects and in many other R & D programs in which the time of product availability is given high priority. The curves demonstrate that as the forecast completion date rises in response to recognition of errors in progress perception, the scheduled completion date is held nearly fixed at its initial value. Two principal changes result:

1. productivity is stimulated to rise significantly, peaking at 1.88 job units per man-month during month 29, an increase of 35% over initial technical productivity;

2. the manpower level on the project is greatly increased, rising up to a value of 44 scientist/engineers from the initial group of 20.

The project is completed by the end of month 34, cutting the slippage encountered in the basic model simulation by almost half. Also significant is that the total manpower effort on the project is reduced to 783 man-months because of the higher technical productivity, saving 5% of the effort of the basic model run.

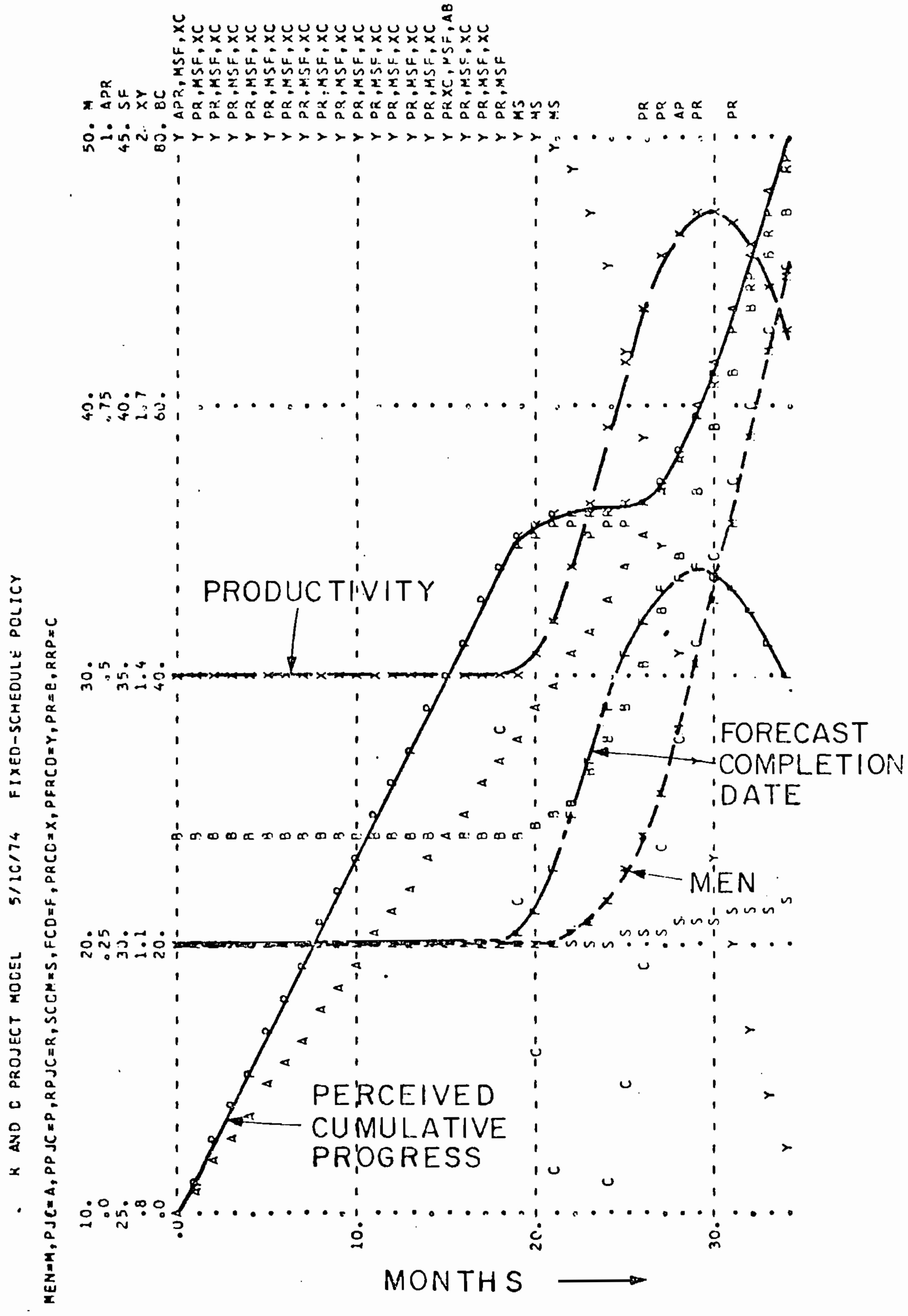

Figure 13. Fixed schedule policy.

Contrasting pattern provides illuminating demonstration of the trade-off between completion time and organization stability. The crash project gets completed in 20% less time than the ultra-stable project, but employs at its peak twice as many scientist/engineers. The high pressure project requires about 10% less total effort than the low pressure case. Generalization beyond these specific computer runs would be dangerous because of the many aspects of increased realism omitted from the model.

Dead-Zone Manpower Change Policy

The final simulation of the model to be reported is one in which company policy toward technical work force change is made wholly unresponsive to small changes in the schedule situation. (This was accomplished by changing the TFCHM table to: TFCHM = -.65/-.4/-.2/0/0/0/.2/.4/.65.) The results, as shown in Figure 14 indicate that no changes in the level of manpower are made during month 29, declining rapidly, however, as schedule adjustments alleviate the pressure. The project is completed by the end of month 40, a 10-month slippage of the original schedule. Total effort required is 793 man-months, reflecting the benefits of higher productivity. Although the manpower stability under the policy is equivalent to that shown in Figure 14, the current case is completed sooner with a lower total effort expended. Both benefits result from the differences in technical productivity generated between the two projects.

Summary of Results

The simple model developed in this paper seems to demonstrate important aspects of research and development project behavior. As illustrated in Table 6, all versions of the model generate significant slippages of planned schedule duration and considerable overruns of total technical effort. Even the hypothesized 'panacea' of perfect progress measurement is seen not to relieve overall performance difficulties in the project.

The principal managerial contribution of this case is its indication of the potential usefulness of dynamic R & D project modeling as a policy design tool. In the modeled project simulations, the trade-offs among various scheduling-staffing policies were chosen as examples of possible management investigation areas. The results of those trade-off analyses were not obvious in advance of the computer simulations. The complexities of R & D projects require some systematic tools that enable policy analysis to be undertaken (Roberts, Weil and Bergan 1973).

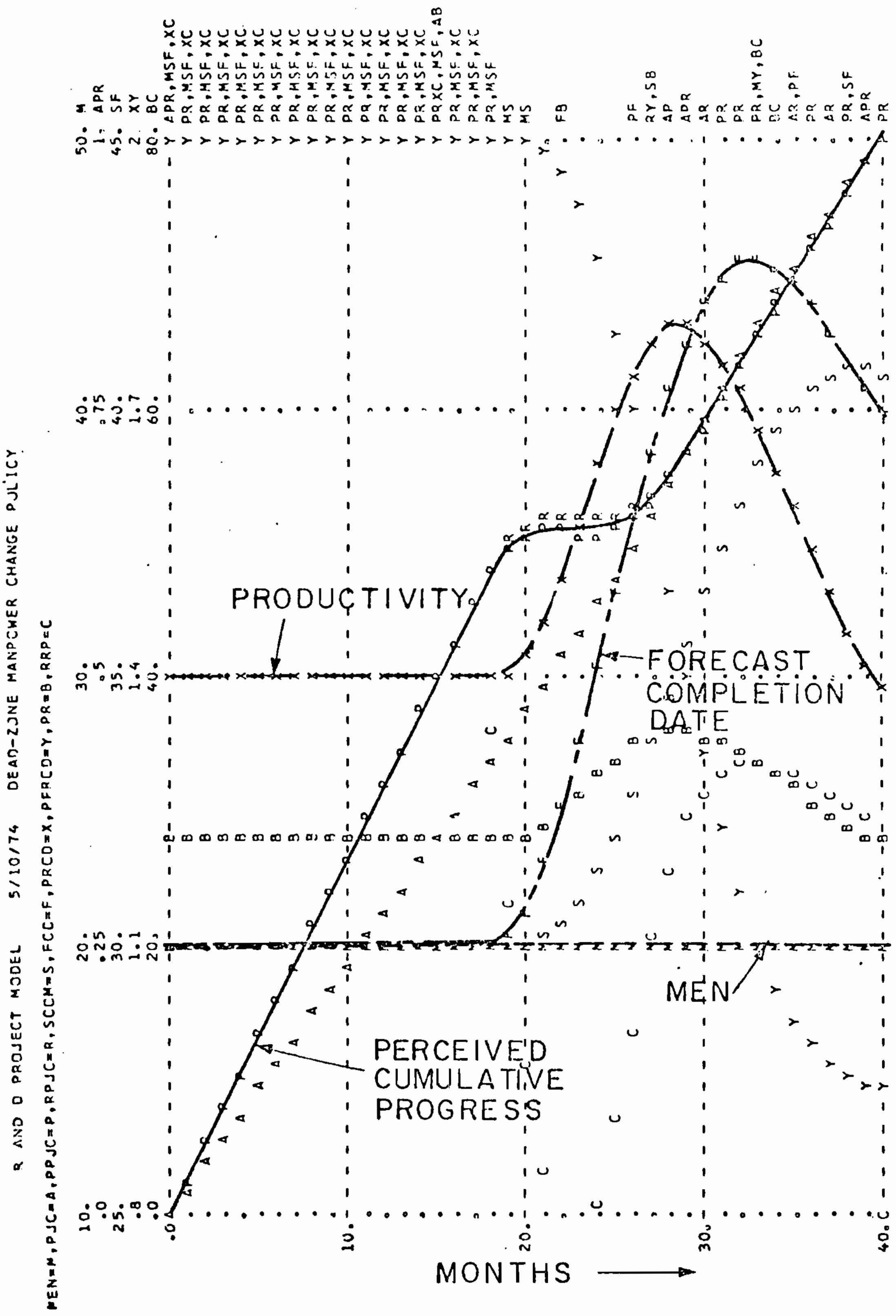

Figure 14. Dead-zone manpower change policy.

Table 6. Comparative project simulation outcomes.

	Project duration (months)	Peak manpower (men)	Total effort (man-months)
Ideal case	30	20	600
Basic model	37	31	822
Accurate progress perception	35	28	831
Immediate schedule adjustments	42	21	853
Fixed-schedule policy	34	44	783
Dead-zone manpower change policy	40	20	793

REFERENCES

Allison, G.T. (1971) Essence of Decision. Little, Brown.

Baker, N., and J. Freeland (1975) Recent Advances in R & D Benefit Measurement and Project Selection Methods. Management Science 21(1).

Brusilovski, B.Ja. (1975) Mathematical Models for Prognostic and Organization of Science. Naukova Dumka, Kiev (in Russian).

Chen, K. (1970) Prolegomenon to Value-Oriented Social Decision Analysis. Battelle Seminar Paper.

Chen, K., M.A. Boroush, K.P. Jarboe, and S.M. Pollock. Inter-fuel Energy R & D Planning: Budgetary Decision Process and Analysis Under Uncertainty. ERD-RR-2. University of Michigan.

Chen, K., C.W. Kirkwood, J.W. Lathrop, and S.M. Pollock, (1977) Energy R & D Modeling for Budgetary Decisions. IEEE Transactions on Systems, Man and Cybernetics. SMC-7(4).

Chen, K., and J.C. Mathes (1978) Value-Oriented Social Decision Analysis. Proposal to National Science Foundation, project established in January 1978.

Dobrov, G.M. (1970) Science of Science. Nauka a Nauke. Naukova Dumka. Kiev (in Russian).

Dobrov, G.M. (1972) Science and Technology Forecasting (Moscow). Translated in the U.S.A. in 1972.

Dobrov, G.M., Ju.V. Ershov, E.I. Levin, L.P. Smirnov. (1974) Experts Estimations for Science and Technology Forecasting, Kiev (in Russian).

Dobrov, G.M., R.H. Randolph, and W. Rauch, eds. (1978) Systems Assessment of New Technology: International Perspectives, Proceedings of IIASA Seminar. CP-78-8. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Forrester, J.W. (1961) Industrial Dynamics, MIT Press, Cambridge, Massachusetts.

Glushkov, V.M. (1969) Forecasting With the Help of Experts Estimations. Kibernetika, Naukova Dumka. Kiev. No. 2 (in Russian).

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

Kingdon, J.W. (1973) Congressman's Voting Decisions. Harper and Row.

Klimenjuk, V.N. (1974) Management of Science Potential Development and Utilization. Naukova Dumka. Kiev. (in Russian).

Linstone, H. and M. Turoff (eds.)(1975) The Delphi Method: Techniques and Applications. Addison-Wesley. Reading, Mass.

Mansfield, E. (1961) Technical Change and The Rate of Imitation. Econometrica 29:741-765.

Pokrovskii, V.A. (1978) Raising the Effectiveness of Scientific Research and Development (Questions and Theory). Ekonomika Moscow. 92-3. (in Russian)

Puch, A.L.III. (1973) DYNAMO II User's Manual.,MIT Press. Cambridge, Mass.

Roberts, E.B. H. Weil, and T. Bergan (1973) The Dynamics of R & D Strategy, in Proceedings of the 1973 Summer Simulation Conference.

Schumacher, F.F. (1973) Small is Beautiful, A Study of Economics as if People Mattered, Blound and Briggs, London.

Sackman, H. (1975) A Delphi Critique: Expert Opinion, Forecasting, Kiev (in Russian)

Tinbergen, J. and H.C. Bos (1962) Mathematical Models of Economic Growth (N.Y.-London: McGraw-Hill).

The Concise Oxford Dictionary, (1972) O.U.P. 389.

Trapesnikov, V.A. (ed) (1977) Management of Research and Development and the Establishment of New Technology) Upravlenie issledovaniami, rasrabotkami i vnedreniem novoi tekhniki. Ekonomika. Moscow. 208.

UNESCO/MINESPOL II/3. Paris. June (1978) 27.

Wildavsky, A. (1964) The Politics of the Budgetary Process, Little and Brown.