# Practical aspects of scientific and technological research programming:

## Case studies from the USSR

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# Preface

The UNESCO series "Science policy studies and documents" forms part of a programme to collect, analyse and disseminate information concerning the organization of scientific research and science policies in Member States, authorized by resolution 2.1131(b) adopted by the General Conference of UNESCO at its eleventh session in 1960 and confirmed by similar resolutions at each subsequent session.

This series aims at making available to those responsible for scientific research and experimental development throughout the world, factual information concerning the science policies of various Member States of the Organization, as well as normative studies of a general character.

Country studies are carried out by the governmental authorities responsible for science policy in the Member States concerned. The selection of the countries in which studies on the national science policy are undertaken reflects the following criteria: the originality of the methods used in the planning and execution of the national science policy, the extent of the practical experience acquired in such fields and the level of economic and social development attained. The geographical coverage of these studies is also taken into account.

Normative studies deal with the planning of science policy, the organization and administration of scientific and technological research and other questions relating to science policy.

The series also includes reports of international meetings on science policy convened by UNESCO.

As a general rule, the country studies are published in one language only, either English or French, whereas the normative studies are published in both languages: reports of international meetings are usually published in the main language(s) used in the region.

The present publication describes some methodological approaches to R&D programming and presents case studies conducted in the USSR. It complements the study entitled *Méthodes de programmation applicables à l'orientation et à la gestion de la R&D nationale* ("Programming methods applicable to the guidance and management of national R&D") published as no. 68 in the same series.

The author is responsible for the choice and the presentation of the facts contained in this book and for the opinions expressed therein, which are not necessarily those of UNESCO and do not commit the Organization.

# Contents

# Introduction

Scientific and technological research activities have always been in the foreground of economic and social life of all industrially developed countries. The scale of the currently conducted research and development (R&D) objectively requires efforts to improve planning activities for securing greater resource payback. One of the means for accomplishing this goal are scientific and technological research programmes. A great number of managers experts and researchers are closely engaged in the elaboration of such R&D programmes.

The concept of R&D programme, its relations with a forecast,a plan and a budget differ considerably in various countries. We shall discuss first of all some methodological problems of R&D programme elaboration. Then, practical applications of forecasting and programming methods in various R&D areas in the Soviet Union will be considered.

# Part I

# Methodological problems of scientific and technological research programming

## 1.1 Classification of R&D planning and management problems

The area concerned with R&D planning and management is very large at present and any classification of the problems in this area is bound to have some shortcomings. Nevertheless, consideration of at least some of the concepts and classifications is required.

R&D has been traditionally classified into fundamental research, applied research and development. Fundamental research is generally defined as research pursuing the solution of problems posed by the very nature of science, conducted with a view to extending human knowledge and understanding the laws of nature without penetrating the field of their concrete utilization. Applied research solves specific practical problems associated with the needs of material production. Experimental development is understood to be an innovative and systematic application of scientific knowledge in the manufacture of materials, mechanisms, systems or methods.

As far as R&D planning and management problems are concerned, the identified classes differ substantially. The formulation of planning goals essentially depends on the opportunity to more or less reliably define the expected R&D outcome. As regards fundamental research, planning implies a considerable degree of uncertainty and risk in the context of expected results. Indeed, many outcomes of fundamental research become clear only after their completion. On the contrary, the expected results of experimental development are generally determined with a great degree of accuracy and credibility. Applied research is, somewhere in-between - the results are defined but with less credibility.

The goals and expected results of fundamental research depend very much on the research staff - their skills, creative capabilities and research background. The researchers' capacities considerably influence the accomplishment of goals. As far as experimental development is concerned, the research personnel hardly influences the attainable goals: one and the same project can be assigned to different groups. As regards applied research, it is in-between the two.

Applied research and development lead time very much depends on the available material resources. As for fundamental research, the allocated resources increase the probability of accomplishing the expected results, but this relationship is not always very close.

Another classification important for the present discussion is that of R&D planning problems with respect to time. They may be classified into forecasting (the elaboration of forecasts), programming (the elaboration of programmes), planning (the elaboration of plans) and resource allocation (budgeting). As applied to fundamental research, forecasting and planning are rather uncertain, hence they are feasible only for a comparatively small time horizon. With respect to experimental development, however, the horizon may be far away.

Elaboration of programmes and plans make sense only for those branches of fundamental research to which considerable resources are allocated. Scientific and technological research programmes are typically drawn up in the field of applied research and experimental development.

Yet another classification may be referred to as being the level of management. The first level is that of research organization management. The second one is management of a cluster of research, design and industrial organizations of a branch of the national economy. The third level is a combination of such organizations from different branches of the national economy. The fourth level exists in the case where organizations represent different countries, international laboratories, joint ventures, etc. In line with the above classification, one is safe in saying that "technological programmes" are developed at 2-4 levels of management: for a number of countries, for one country (region, several industries), and for an individual branch of the national economy.

## 1.2 Classification of methodological approaches

There is a great variety of methodological approaches to the consideration of R&D activities. Successful application of one or other R&D programming method and the validity of recommendations derived therefrom depend on how well they match specifics of the research activities to be considered or the problem to be solved.

R&D forecasting and programme planning at the national and sectorial levels share the following common characteristics: comparative evaluation of alternative decisions are difficult to make; presence of a set of non homogeneous factors to be taken into consideration; non-recurring choice situations making it impossible to act "by analogy", and inadequate certainty of the decision implications.

In the course of R&D forecasting and programme planning, many characteristics of the considered problem or object under study can be described with objective data (factual, statistical, planning, reporting, recording, etc.) and objective models which represent the basic attributes of the problem or object in quantitative terms. The available methods of processing the quantitative input information allow one to expose regularities and interrelationships of different factors, and estimate the trends in indicator variation.

The objective information does not suffice, however, for R&D forecasting and planning. The presence of uncertainty complicates the search for a unique, objectively the best (optimal) decision, and necessitates consideration of the decision-maker's (or a group thereof) preferences, i.e. subjective information. Another source of subjective information are skilled experts possessing profound knowledge. Reliability of expert information must be secured by special procedures for its elicitation and by adequate processing methods to deal with the specifics of the considered problem.

A methodological basis for R&D forecasting and programme planning is provided by the systems approach which regulates the basic logical steps of the problem investigation procedure:

- differentiation of the system under study from external environment;
- problem definition and its quantitative and/or qualitative description;
- defining possible methods of solving the problem;
- development of alternative problem solutions;
- comparison of alternative options and choice of the best one.

This general scheme is specified in quite different ways by operations research, systems analysis, and decision techniques, aimed at developing rational approaches to, and procedures of problem study.

*Operations research* focuses on the quantitative description of the considered problem and/or object (well structured, as a rule) and the construction of a model, and on quantitative methods of finding the best solution.

*Systems analysis* deals with ill-structured problems, and the major emphasis is placed on the analysis of goals, transition from goals to means, and the quantitative or qualitative evaluation of the goal accomplishment alternatives.

*Decision-making* furthermore examines ill-structured or non-structured problems. The major purpose is the alternative evaluation and comparison with a view to: determining the best solution alternative; ranking the alternatives; and classifying the considered alternatives into several decision groups.

In R&D forecasting and programme planning wide use is made of the aforementioned approaches. Let us consider the most widespread techniques within the context of the systems approach.

## 1.3 Forecasting and analysis of development trends, and validation of the master goal

Analysis of the present state and future development of a system or object under study is an opening step of problem solving referred to as an exploratory stage of forecasting. The analysis focuses on trends in the evolution of the system, and identifies possible relationships between the trends and changes in the external environments. The purpose of the analysis is to provide a basis for the more valid definition of the final (master) goal or a set of system development goals. Hence, the major requirements to exploratory forecasting are the systematization of trends and a sufficiently detailed description thereof. The following problem solving techniques are noteworthy in this respect:

- extrapolation of trends;
- development of scenarios;
- the "Delphi" technique.

*Extrapolation of trends* is one of the most widespread forecasting methods, involving the analysis of "time-variation" dynamics of identified variables (time series). Use is made of both rather simple methods of linear extrapolation and complex extrapolation techniques with the application of econometric models. The principal shortcoming of extrapolation techniques is their low reliability for distant forecast horizons, associated with the impossibility of accounting for qualitative changes in the projected system and forecast background.

The *scenario method* is used for describing the logical sequence of events which projects the future state of the original situation. Along with writing a scenario, one may consider different aspects of the problem, identify critical events and branching points, giving rise to alternative development options, and focus on the key aspects to be scrutinized in more detail. Scenarios provide an opportunity for drawing a systematic picture of a probable future state. One of the shortcomings of the scenario method is a subjective choice of development hypothesis inaccurately reflecting the "reality" which may lead to an erroneous or distorted "picture of the future".

*The "Delphi" technique* boils down to identifying a collective expert opinion concerning the development trends of the system and/or problem under study. The experts are usually interviewed with questionnaires. The answers are given in the form of quantitative characteristics. Interviews are carried out in several steps, each one followed by a statistical processing of data and specification of questions. The experts are informed of the results at each step, and requested to substantiate their opinion, and to specify their estimates with regard to reasoning of their associates. As a result, the expert estimates become less scattered, and a consensus of opinion is developed.

Thus the "Delphi" technique makes it possible to harmonize professionals' opinions on a wide range of issues. However, the practical application of the method is rather difficult. First, the quality of the final result is considerably affected by the list of questions and clarity of definitions which largely depends on the experience and skills of the organizers of the "Delphi" survey. It is not ruled out at all that experts may be influenced by the questionnaires. Second, there is a certain "mixture" of heterogeneous opinions held by experts of different skills. Third, the opinion of the majority is not always a guarantee of truth, and the discarded judgements of the "dissident" experts may well be more correct. Fourth, the available procedures of expert grouping and statistical assessment of expert estimates processing are inadequately substantiated.

The master goal or a set of system goals is a result of political choice based on the exploratory forecast. This procedure is rather poor judged from the methodological point of view. Very often, a master goal is formulated in the most general form, almost as a slogan or motto. The poor specification of the master goal prevents the decision-maker from controlling the validity of the transition to subgoals of lower levels, and from consciously developing R&D policy alternatives.

Very often, there are several equal goals at the upper decision-making levels. Under these circumstances, an artificial choice of one of them, or formulation of a hypothetical goal of a higher level may lead to a substitution of the actual decision-maker's preferences by a formal construct imposed by the selected methods.

Taking into account the basic tasks of the exploratory forecast and the uncertain character of the events under study, one may conclude that most acceptable for the analysis of development trends are qualitative techniques, while quantitative approaches must play a supportive, auxiliary role.

Effectiveness of the analysis and validity of the master goals selection considerably increase if the decision-maker directly participates in formulating a "frame" for the forecast, defining requirements as to its content and form of presentation, and choosing the most significant goal-attainment evaluation criteria.

The major methodological tasks of trends analysis and master goal selection are as follows:

- it is necessary to clearly define the structural frame of the forecast and the range of questions it covers;
- there is the need for logical analysis, making it possible to structure the procedures of defining the master goal or a set of goals at the upper decision-making levels; and
- the decision-maker and experts must closely interact in formulating a forecast and compiling an exhaustive list of master goals.

### 1.4 Transition from final goals to the means of their accomplishment

The means of goal accomplishment are determined at the second stage. There are two basic types of problem concerned with transition from final goals to subgoals and means of their achievement: defining a set of means securing attainment of the earlier assigned goals ("downward" transition), and defining a set of goals that can be accomplished with the specified means ("upward transition").

Transition from goals to means of their accomplishment involves definition of hierarchy levels, sets of components at each level, and relations between them. The most widespread are the following methods binding together goals and means:

- construction of relevance trees;
- hierarchical structuring;
- matrix techniques;
- morphological analysis.

*Relevance trees* gained wide acceptance in constructing logical sequences of transition from a master goal to lower-level subgoals. The major tasks, evolving herewith, are associated with determining the number of tree apexes and levels, and evaluation criteria. There are no clearly defined principles for selecting the number of a tree levels and attributing an element to a certain level. This is usually done on the basis of general statements or the available classifications of system components. For each subgoal of the given hierarchical level they develop a maximum set of possible components of the next level providing for the achievement of the considered subgoal.

Very often, relevance tree construction is followed by a quantitative assessment of its components by methods described below (assignment of weights, relative significance coefficients, ranking, etc.). As a rule, evaluation criteria are also weighted. The absence of explicit criteria of relevance tree construction leads to a situation in which a variety of "equivalent" relevance trees may be built for an assigned master goal. Besides, completeness of the list of components of each level is not guaranteed and, naturally, some important relationships between the levels may drop out from consideration.

*Hierarchical structuring techniques* are used for defining sets of interrelated subsets of objects (connecting graphs) making it possible to exercise a consistent "logical" transition from goals to means of their accomplishment. The relations between the adjacent levels of a hierarchical structure, different from a tree, are determined by the logic of the considered system (fields of science, resource planning, allocation systems, etc.) to which the given technique is applied.

In order to distinguish hierarchical levels and refer the components to each level, it may become necessary to formulate criteria reflecting the policy of the planning body. As applied to various techniques of hierarchical structuring, the relations between the components of different levels may be quantitative (contribution coefficients) or qualitative. Ignorance of the general principles of components differentiation at each level may lead to distortions in the logic of structure formation, and to conflict between the assigned and actually accomplished goal. It should also be kept in mind that small changes at the upper levels of hierarchical structure or relevance tree may entail considerable changes at the lower levels.

*Matrix methods* ("goals-means" matrices, influence matrices, decision matrices, etc.) are used for evaluating the significance of different means in accomplishing a set of goals or an individual goal. First, the entire variety of factors, determining the achievement of goals, are divided into rather uniform groups. Then they measure the impact the group components exert on one another and on the accomplishment of final goals by ranking or weighting the components within each group. The contribution and interdependence of different ways of accomplishing the goals is determined by operating on the matrices whose elements are the estimates of influence of elements of the i-th group on elements of the j-th group.

The matrix techniques feature the same advantages and shortcomings as the approaches considered above. A large number of components and groups are fraught with additional difficulties associated with the large dimension of matrixes.

*Morphological analysis* is an ordered method of problem and/or object study with a view to systematic organization of information on all alternative solutions and selection of an acceptable solution. The basic steps of morphological approach are a clear statement of the problem; identification of all factors determining its solution; an ordered analysis of factors and the construction of so-called "morphological box" containing all possible decisions; and evaluation of functional utility of different decisions and choice of the most preferable ones.

One of the advantages of the method is the possibility of its application given a relatively small amount of input information and rather general decision evaluation criteria. The major drawback is associated with the method of building the "content of morphological box" where possible decisions are obtained by multiplying the distinguished factors located in the lines of the "box." Therefore, there can be a considerable number of actually unfeasible decisions. Besides, the method employs an extremely simplified approach to evaluating and comparing alternative decisions.

The methods of developing the means of goal accomplishment make it possible to formulate alternative solutions, analyze the contribution of different factors to the accomplishment of goals, and allocate the available resources. Hierarchical structuring may be recommended as the most preferable approach to building the means of goal achievement and defining the total amount of resources required.

Definition of transition from goals to means of their accomplishment, and evaluation of system or object components are typically carried out by the expert technique. To secure the best substantiation of transition, it is desirable to involve senior managerial personnel of the planning body.

To construct techniques for transition from goals to means of their accomplishment it is required to solve the following methodological problems:

- to have a valid approach to defining the number of hierarchical levels or groups of components;
- to have a method of building sets of components at each level or in a group, and to secure the complete lists of those components;
- to develop criteria for estimation of relationship within levels or groups.

## 1.5 Evaluation of goals and the means of their accomplishment

Relevance trees, hierarchical structures, and matrixes used in R&D forecasting and planning contain a large number of levels or groups of components, a considerable quantity of components in each group, and complex interrelationships of components from different levels and groups. The system is usually so complex that it is practically impossible to present, in analytical form, the dependence between the system components' characteristics and to take account of the cross-impact of numerous factors. The assessment of components of each level and relations between them, which will be behind the comparative analysis of alternative means of goal accomplishment, is therefore an important stage in problem-solving.

Such information is generally provided by skilled professionals — decision-makers or experts. Depending on the number of information sources, one distinguishes between individual and collective assessment techniques.

Elicitation of necessary information breaks into two stages:

- compilation of a list of criteria against which components and relations between them are estimated;
- evaluation of components and relations by the available criteria.

It is assumed, while formulating the criteria, that there is an explicit and implicit idea about preference (values, priorities, etc.) of evaluated systems or objects.

A great variety of expert judgement techniques, depending on the nature of the information, and on methods of its elicitation and processing, are classified into:

- quantitative evaluation techniques;
- qualitative evaluation techniques.

In different techniques for quantitative evaluation of alternatives the "general utility" of alternatives considered is prescribed (*a priori* or axiomatically) and the parameters of this utility dependence are either assigned or directly evaluated by the decision-maker. There are the following most popular methods of quantitative evaluation:

- ranking, when each alternative is assigned some number (rank) which indicates the place of the alternative within a set of alternatives;
- weighted sum method where the utility of the j-th alternative is determined by the function

$$U_j = \Sigma_i C_i X_{ij}, \ \Sigma_i C_i = 1,$$

  where $C_i$ is weight (significance) of the i-th criterion, $X_{ij}$ is an estimate of the j-th alternative against the i-th criterion;
- multiplicative method when utility is determined by the function

$$U_j = \Pi_i C_i F(X_{ij}),$$

  where $F(X_{ij})$ is an individual preference function, most often $F(X_{ij}) = X_{ij}$, less often $F(X_{ij}) = \exp\{X_{ij}\}$, or another function;
- interpolation of utility functions with different types of function where parameters are assigned in advance or defined on the basis of the decision-maker's preferences;
- evaluation of subjective event probabilities on decision or preference trees where utility of the j-th alternative is defined by the formula

$$U_j = \Sigma_i P_i X_{ij},$$

  where $P_i$ is the subjective probability of event $X_{ij}$.

Various approaches are used for determining weights $C_i$, for example, direct definition of relative weights (in particular, by "Delphi"-type expert techniques), successive determination of weights (Churchman-Ackoff method, etc.), pairwise comparison of criteria (Terstone method, etc.), on hierarchical ranking of criteria, etc. Subjective probabilities $P_i$ are evaluated directly or by a lottery method.

On the whole, quantitative assessment of alternatives is an insufficiently correct and valid procedure as it does not take account of the possibility of eliciting reliable information from decision-makers and experts.

The basic idea of qualitative evaluation techniques (against many criteria, as a rule) boils down to utilizing a natural language for expressing decision-makers' preferences, expert judgements, and the determination of alternatives' utility. As a rule, each criterion has its own estimate scale with extended or brief verbal statements of different characteristics of the problem or object under study. Selection of criteria and construction of estimate scales constitute a non-formalizable task whose solution depends on the skills and experience of the systems analyst. At the same time, decomposition of general quality into criteria is not only a method of problem analysis but also an effective tool for obtaining information.

Development of a set of criteria for assessing the components of each hierarchical level, relations of components, and generation of estimates against the available criteria is of special significance as the credibility of this information decisively affects the outcome.

Most R&D forecasting and planning methods use numerical estimates of components of all hierarchical levels ("weights", contribution coefficients, relative significance, etc.). In case a method employs qualitative estimates, they are immediately put in correspondence with numerical scales. Psychological research indicates, however, that numerical evaluation of ill-defined qualitative factors is too complex for people and often leads to unstable and inconsistent estimates.

Multicriteria qualitative assessment of a task or object is most consistent with the nature of R&D forecasting and planning problems. Criteria and scales of their estimates constitute a convenient and customary language of interaction between managers and experts, which makes it possible to represent decision-maker's preferences and to formulate the scientific and technological policy of planning bodies.

The analysis of approaches to evaluating goals and ways is conducive to formulation of the following methodological problems:

- it is necessary to develop correct techniques for information elicitation and processing consistent with the nature of the tasks solved;
- the decision-maker should directly participate in selection of experts and development of criteria and their scales for evaluation of the components at all levels of the hierarchy.

## 1.6 Comparison and selection of alternative ways

In making a comparative analysis of feasible alternatives (sets of ways for accomplishing the goals) and selecting the most preferable option, one has to formulate a decision rule which may have the form of an aggregate estimate of components, criteria of choice, or formal procedures. Auxiliary procedures employed in the alternative comparison and selection techniques are pairwise comparisons and classification.

Pairwise comparisons are a procedure for defining preferability of alternatives in comparing all possible pairs of objects and attributing each pair of alternatives to one of the assigned classes. Comparison of all possible pairs does not guarantee a complete ordering of objects, hence an additional identification is required. Under multiple comparisons, triples, quadruples, n-s of alternatives rather than pairs are subject to a successive comparison.

Classification (grouping, taxonomy) is a procedure of breaking a set of objects into classes (groups). Attributing an object to some class or other is carried out directly or on the basis of decision rules taking account of the object preference. The number of classes may be prescribed in advance, or determined by the properties of analysed alternatives.

In making use of pairwise and multiple comparisons, and of classification procedures one has to take into consideration that there may exist noncomparable alternatives, and "inconsistency" of an expert in presenting his preferences, leading to a distortion of transitivity.

The methods of the best alternative choice (decision techniques) differ in the ways of transition to a general assessment of alternatives' utility. There are the following groups of such methods:

- the axiomatic approach;
- direct assessment methods;
- compensation techniques;
- comparison thresholds techniques;
- mathematical modelling;
- descriptive-normative methods.

The axiomatic approach, based on the utility theory, substantiates the existence of utility function which characterizes the degree of alternative preferability. The form of the utility function is determined by the systems' properties assigned by axioms. There are axioms of "poor order" and transitivity, axioms of independence with respect to utility, axioms excluding anomalies in preferences, and so on. The most frequent use is made of additive and multiplicative utility functions of the form

$$U(X) = \Sigma_i K_i U_i(X_i), \qquad \Sigma_i K_i = 1$$

or

$$1+KU(X) = \Pi_i [\, 1+KK_i U_i(X_i) \,], \; \Sigma_i K_i \neq 1,$$

where $U_i(X_i)$ are utility functions of alternative $X_i$ against individual criteria, and K and $K_i$ are constants ($0<K_i<1$, $K>-1$).

Verification of utility function correctness is carried out by eliciting information from decision-makers. It is verification of the axiomatics feasibility that is most difficult in practical application of axiomatic techniques as it requires special training of decision-makers and special procedures for their interrogation. It is worth noting on the whole that axiomatic methods are rather artificial.

In contrast to axiomatic techniques, largely oriented at substantiation of some or other type of utility function, the direct assessment methods postulate the type of alternative general utility without any substantiation. The most widespread direct methods are:

- generation of an aggregate quantitative estimate on the basis of an *a priori* assigned multicriteria utility function (methods of weighted sum of criteria estimates, decision trees, and other methods considered above);
- formulation of a generalized choice criterion — "cost-effectiveness" criterion, optimality criterion (maximin and minimax pessimism criteria; maximax optimism criterion; pessimism-optimism criterion (Hurwiz criterion); average gain maximum criterion, etc.);
- lexicographic ranking of criteria, when an alternative with the highest estimate by the most important criterion is considered as the best one.

Axiomatic methods and methods of direct assessment usually result in complete ranking of decision alternatives. Note that the task dimension does not matter. Problems of alternative comparative assessment have, as yet, no solution thus far, as applied to dependent criteria.

Compensation techniques are based on a trade-off between the conflicting estimates against a pair of criteria or more. This group of methods comprises:

- balancing (compensation) of alternative estimates against different criteria;
- plotting of points, curves, and indifference surfaces in a criterion space;
- comparison of alternative estimate differences (on the basis of utility function, pairwise comparison, etc.).

Compensation techniques usually result in a quasi-order of a set of decision alternatives. Intransitivity may arise in alternative estimates, requiring special procedures of preference verification.

The comparison threshold techniques (ELECTRA and other methods) exercise pairwise comparison of alternatives making use of binary relations between decision alternatives which determine preferability, equivalency, or noncomparability of alternatives. Under changing conditions (comparability thresholds) the resulting relations of alternative preference change too. In making use of comparability threshold methods, one distinguishes a class of the best decisions containing considerably fewer alternatives than a Pareto set. In applying the methods account should be taken of the fact that the types of binary relations and their sequence considerably predetermine the choice.

Mathematical modelling is a method of searching for effective solutions of problems partially formalized on the basis of an objective model; the model variables and relations thereof are defined. The task is to find the best criteria ratio attainable on the given model. As a rule, such problems are formulated as multiattribute mathematical programming problems (linear programming, vector optimization, task-oriented programming, etc.).

There are many man-machine procedures for their solution, where the decision-maker specifies the characteristic features of the problem, identifies and specifies his/her preferences, supplies additional information until he/she accomplishes an acceptable solution. With respect to the type of man-machine interaction, the procedures are classified into three groups:

- direct procedures when the decision-maker exercises a direct search for a preferable solution (SIGMOP procedure);
- vector evaluation procedures when the decision-maker evaluates the utility of alternative solutions in the form of vectors in a criteria space (Dyer-Gioffrion, Savir, Zionts-Wallenius procedures, etc.);
- procedures of search for satisfactory criteria values when the decision-maker performs the search for a preferable solution by imposing and changing constraints on criteria values in the solution point ( STEM, Belenson-Kapur, external branching, satisfactory goals procedures, etc.).

The results achieved by mathematical modelling to a considerable extent depend on the model adequacy to the real situation. The key here is construction of correct methods of obtaining information from people.

Descriptive-normative methods explore possibilities for eliciting reliable, consistent information from people (decision-makers, experts). Special psychological research into the human information processing system underlies the methods.

The psychological studies carried out all over the world in recent years make it possible to evaluate different approaches to eliciting information from humans and to determine correct operations, for example, comparison of alternative values against two criteria, criteria ranking with respect to priority, etc. The employed procedures of direct and indirect elicitation of information make it possible to check the decision-maker's responses, and find and remove inconsistencies on the basis of additional considerations. Qualitative notions elicited from decision-makers and experts remain intact during information processing, without any transition to numbers right up until accomplishing a desired result. The examples of descriptive-normative methods, the ZAPROS (Closed Procedures by Reference Situations) method, and the method of direct classification CLASS, are described in Annexes 1 and 2.

Comparison and choice of the best decision alternative is a closing step of any R&D forecasting and programme-planning method. Despite the fact that rule formulation procedures for making decisions differ in various methods, the overwhelming majority of the latter share common methodological shortcomings, such as:

- qualitative indicators are used for evaluation and choice of alternatives;
- expert estimates are treated as objective information subjecting them to different mathematical conversions;
- there are "pseudo-objective" mathematical models of estimate aggregation having no descriptive substantiation;
- many relationships are far from indisputable and are formulated by different methods;
- insignificant changes in the model regulations may decisively affect the ultimate result.

The major methodological problems to be given attention at the current stage are as follows:

- it is necessary to use correct methods of information gathering and processing when comparing and selecting the alternatives;
- the decision-maker must participate directly in the development of comparison and selection criteria;
- methods for the aggregation of estimates, and for the comparison and choice of alternatives must operate on decision-makers' preferences, as well as provide for a stagewise monitoring of "best decision" development and for adjusting the process of selection.

## 1.7 Analysis of programme-planning methods

The programme-planning methods are, in effect, labour engineering procedures applied to the activities of managers and staff of planning bodies, analysts and experts. To compare the methods from the methodological standpoint it is necessary to formalize the comparison criterion. This criterion must be closely linked with the general purpose of the method application. Hence, the following requirement may be set for programme-planning techniques.

A transition from global goals through ways of accomplishing them to resource allocation decisions, the programme-planning procedure must allow decision-makers to control all the consequences of accepting different information from experts, and formulating various decision rules.

Comparison of the existing techniques with respect to meeting this requirement will, in effect, be their comparative assessment against the criterion characterising practical utility of the method. Indeed, successful practical application of the method is evinced by the extent to which it increases the actual influence of the top manager on decision-making. In analysing, we shall follow the above-mentioned stages of the systems approach. These stages are not obligatorily part of each of the programme planning methods, but they are found in many of them.

The analysis of trends in system development and in forecast background changes is a mandatory stage only for some of the methods (PATTERN, PROFILE, QUEST, PPB, CPE and forecast graph method). Thus in PATTERN and CPE methods the forecast covers 10-15 years. The forecast horizon in the forecast graph method is 15-25 years. In order to expose internal development regularities, use is usually made of scenario and expert judgement methods. To study the dynamics of the forecast background use is made of analysis of factual information, extrapolation of trends, and classification of events.

The major methodological shortcoming of many R&D programme-planning techniques is poor linkage of exploratory forecast with the needs of the planning body with regard to selection and validation of the master goal. The PATTERN, CPE, TORQUE and other methods give little attention to substantiating the master goal which is treated as if natural and evident.

The principal purpose of R&D programme-planning techniques is the construction of a successive transition from master goals to means of their accomplishment. The most widely accepted approach is the construction of relevance trees (PATTERN, PROFILE, TORQUE, CPE, etc.). There are also hierarchical structure methods (PPB, ZAPROS, etc.) and matrix methods (QUEST, RDE, etc.).

An extensive literature on R&D programme-planning techniques practically neglects the issues of selecting the number of levels of relevance tree or hierarchical structure and the number of groups of homogeneous components. The PATTERN designers only indicate that the number of relevance tree levels depends on the quantity of assignments, and on the depth and concreteness of the research plan. They do not offer any concrete recommendations or any methodological principles that could provide a basis for such recommendations.

With a view to constructing relevance trees, the majority of known methods make use of similar procedures involving definition of a master goal and subsequent systematic transition to complete sets of subgoals of lower levels. The components are attributed to some level or other on the basis of their relations with (contribution to) the higher-level components rather than belonging to a certain class of objects. Hence, components of a different nature may happen to be on one and the same level.

A certain step forward, as compared with the relevance tree methods, are hierarchical structure and matrix methods where attribution of components to some group, and relations between components are determined by the internal structure logic of the planning system (of field of science) applying the given method; thus for example QUEST, developed by UNESCO for priority determination in science and technology. In this method three groups of objects are differentiated: military problems, engineering sectors and scientific branches. Each one has its own classification attribute. Relationships between objects of different levels are evaluated with respect to contribution coefficients. Nevertheless, hierarchical structure and matrix methods may involve cases of illogical aggregation of components at different levels which are caused by distortion of the unified principles of component differentiation at each system level.

Consideration of the most popular R&D programme-planning techniques leads to the conclusion that very often they lack explicit criteria providing a basis for determining the number of hierarchical levels, and evaluating communications between the objects of different levels. An exception is the hierarchical schemes method where criteria are formulated on the basis of the decision-maker's preferences.

The principal step in developing programme-planning techniques is the compilation of a list of criteria against which the components of each level are to be assessed. As a rule, different criteria are employed at different levels of the hierarchy. Components of different levels are typically estimated by different groups of experts.

The majority of programme-planning techniques evaluate components in numerical terms ("weights", contribution coefficients, impact, significance, relative importance, probability of goal accomplishment, occurrence of events, and the like). As was mentioned above, however, the application of numerical variables to assessing complex and differently interpreted characteristics (such as "R&D perspectiveness", "fundamental significance", "contribution to the solution of applied problems", etc.) reduces reliability of the acquired information and, in the final count, the practical utility of recommendations generated with the method.

A considerable shortcoming of many R&D programme-planning methods is that criteria are developed without the decision-maker's participation. Since the manager has to resort to expert assistance for obtaining some or other estimates, the criteria and scales of their assessment are, then, a language for decision-maker-expert interaction. Under these circumstances, the decision-maker's confidence in expert information is possible only in the case where the manager directly participates in selecting the experts and developing the object assessment criteria and scales thereof.

Development of a decision rule for comparing different decision alternatives and selection of the best option differ in various R&D programme-planning techniques. In many methods estimates of components are aggregated in a single numerical coefficient of importance. The general measure of significance for some task at any level of a relevance tree is computed, in the PATTERN method, by multiplying the rated coefficients of relative significance upward the relevance tree. Similar procedures of component estimate aggregation are employed in PROFILE and TORQUE techniques. As far as PROFILE is concerned, the utility of tasks is different for each of the selected sectors, while in TORQUE the measure of significance is computed for each element of the lower level.

As for the CPE method, it makes use of the more simple and concrete method of table construction rather than quantitative measures of contribution. A subgoal utility assessment is carried out by experts in utility classes. In this case too, however, a relative "importance" of criteria is determined in numerical form for estimate aggregation, and the utility classes themselves are treated as estimate weights.

In the field of advanced research programme-planning, so difficult to formalize, wide use is made of mathematical models, often rather complex. In such models, numerical expert estimates of qualitative factors (such as "fundamental significance" or "correspondence to the organization profile") are employed in various mathematical conversions along with objective quantitative values subject to precise measurement (e.g., annual cost of project, number of researchers at the institute, etc.). Utilization of such inhomogeneous information in one model seems rather risky and incorrect methodologically.

The decision-maker's role in programme planning typically boils down to discussion and general statement of the task. Development of the method structure, systems of criteria, and defining the form of the decision rule is, generally, carried out without decision-maker's participation. As a result, the latter is offered the "best" unique solution. And he/she remains ignorant of the information conversion. Therefore, the mistrust of the planning body management to the thus developed recommendations seems quite natural. The attempts to identify decision-maker's preferences, by assigning numerical "weights" to criteria, change essentially nothing.

On the whole, the use of numerical measures in R&D programme-planning for evaluation and selection of alternatives seems unreasonable and inadequate to the considered problems. A greater decision-makers' confidence in the final results is secured by the methods making use of correct procedures of information collection and processing, based on decision-maker's preferences, allowing the decision-maker to control all stages in decision preparation and making, and to estimate the consequences of the decision made. This is the case in ZAPROS or CLASS methods.

# Part II

# USSR case studies

## 2.1 Forecasting applied research and development

### *Goals*

The major part of the scientific and technological potential is concentrated in the productive sectors of economy. The sectoral R&D organizations conduct the lion's share of applied research and the overwhelming majority of experimental development projects, as well as some fundamental research largely oriented toward the solution of sectoral problems. The R&D conducted by industries is one of the major links in the process of "science-innovation-production" and should provide the materialization of technological advances and their utilization in economy. The scale and benefits of the applied R&D depend to a considerable extent on the resources allocated.

A general forecast of advances in sectoral science and technology is built on the basis of exploratory forecasts of R&D in individual industries. The data obtained must be generalized in accordance with the scientific and technological policy of the management bodies (USSR State Committee for Science and Technologies, Ministries, USSR Academy of Sciences, etc.) with a view to integrating and harmonizing different alternatives of economic development. The basic purposes of forecasting by this method are:

- selection of advanced directions of applied R&D;
- analysis of R&D resource supply in the branches of economy.

### *Approach employed*

In conducting a comparative analysis of sectoral research use is made of a special generalized logical model whose principal building blocks are: economic objectives of sectoral development, directions of R&D, scientific and technological problems, and resources.

The objectives (goals) of sectoral development are determined by analysing the general trends in socioeconomic development of the country and projecting changes in production and consumption patterns. These objectives are formulated in a rather general form and take into account the interests of the national economy as a whole, possible resource constraints, as well as consistency with the "rank" of the industry in the national economy in the long run. Besides, the objectives of different industries may be expressed quantitatively in terms of specific indices of production and/or consumption.

The directions of R&D are the aggregates of scientific and technological research tasks providing for a technological solution of sectoral problems. The R&D directions are differentiated by analysing the current R&D state-of-the-art with regard to the future objectives of the industries and the existing resource constraints.

Scientific and technological research tasks, treated as the means of development goals accomplishment, are formulated within each R&D direction. An R&D task is defined as an integration of R&D activities oriented toward a concrete ultimate result (development of a machine with specified parameters, a manufacturing process ensuring the required accuracy, quality, etc.). Scientific and technological research tasks have both quantitative estimates (approximate costs, lead time, effectiveness) and qualitative characteristics. The relationships between quantitative and qualitative variables cannot be uniformly prescribed, hence, it is difficult and, more often, impossible to evaluate the overall significance of the task. What is more, the value of an individual scientific and technological research task will depend to a considerable extent on the national economic objectives it is supposed to accomplish.

Staffing and funding of sectoral R&D organizations, their experimental facilities and pilot plants are considered as resources in the model. The basic characteristics of scientific and technological potential are described by the indices specified by the statutory forms of the standing national accounting system.

Development and assessment of the components of the logical model are carried out with the help of managers and skilled professionals from ministries and agencies, leading sectoral research institutes on the basis of exploratory forecasts of development of sectors of economy, forecasts of individual branches of science and technology, foreign and national scientific and technological information, patents, statistical data, research programmes and plans.

The lists of long-range sectoral economic objectives, directions of R&D, scientific and technological research tasks are compiled by the parent sectoral research institutes and agreed upon with the industry administration (ministries, agencies). Qualitative and quantitative criteria are established for evaluating scientific and technological research tasks and their contribution to the solution of sectoral objectives. Experts' interviews are conducted for each sector separately, in line with a special procedure making use of expert analysis charts.

### *Criteria*

The scientific and technological research tasks are at present characterized by the following scaled criteria:

A1. Task orientation with respect to its contribution to the solution of the major national economic objectives.
A2. Area and scale of R&D outcome application.
A3. Comparison with foreign level.
A4. Availability of research backlog for accomplishing the task.
A5. Approximate time of task accomplishment.
A6. Expected economic payoff.
A7. Approximate cost of task solution.
A8. Required resources.

A part of the criteria have quantitative scales while others are qualitative. With some criteria one is allowed to use both quantitative and qualitative estimates depending on the available information. Qualitative criteria have different types of scaled structure. For example, criterion A1 scale looks as follows:

A1. Task orientation with respect to its contribution to the solution of the major national economic objectives:

a. labour saving;
b. energy saving;
c. saving and substitution of scarce raw materials;
d. improvement of product quality;
e. solution of ecological problems;
f. solution of social problems;
g. solution of organizational and technological problems of the industry.

### *Method*

The choice of applied R&D directions is based on a comprehensive comparative analysis of scientific and technological research tasks coped with in the context of the aforementioned directions and in conformity with the scientific and technological policy. The long-range scientific and technological development policy of an industry may take the form of requirements to the applied R&D output which may in turn necessitate the solution of certain national economic problems within the projected period. Account should also be taken of R&D economic benefits. Priority is given to tasks making the greatest contribution to the accomplishment of the assigned targets.

It must be kept in mind, however, that the scientific and technological development policy of different ministries may sometimes not be fully consistent with the more general goals of national economic development, and/or disregard resource constraints and their allocation.

Definition of the scientific and technological policy is the most important phase in the process as the chosen alternative R&D policy bears decisively upon the ultimate result. The choice of goals, their definition in a general form and transition to sets of criteria estimates must follow a thoroughly thought out procedure, and be carried out with direct decision-maker participation.

The scientific and technological policy alternatives are suggested by the sectoral and industrial management body or manager in the form of estimates against criteria A1 -A8, or combinations thereof. For example, "Primary attention within the projected period should be given to the R&D directions which provide for a significant saving of labour, improve solution of ecological problems, ensure much higher quality of product (criterion Al). It is highly desirable to secure a certain ratio between the task solution costs and benefits (criteria A6, and A7) and the task accomplishment by a certain date (criterion A5)". Referred to as priority are the scientific and technological tasks having the required combinations of estimates against the listed criteria.

The decision-maker could evaluate the consequences of the choice of some or other alternative policy, sort out the respective lists of tasks and directions and, if necessary, adjust his requirements with regard to circumstances.

The priority analysis of scientific and technological research tasks was conducted for the entire national economy, for clusters of industries, and for individual sectors. Subject to analysis were several alternative scientific and technological policies. The compiled list of perspective R&D directions and priority research tasks made it possible to define the industries, research and technological organizations working on given research tasks, and to assess the resource supply.

In analysing scientific and technological potential in industries, and assessing its development trends, use was made not only of data on the prospects of applied R&D directions, but of a number of other statistical indices. These are the share of people engaged in R&D in relation to the total manpower of the industry; the ratio between science expenditure and product output in monetary terms; the share of researchers holding academic degrees in the total R&D personnel; and some others.

In forecasting resource supply needed for R&D in the various branches of the national economy, account was taken of the scientific resource development forecast for the country as a whole; of the necessity of removing disharmonies in the scientific and technological potential of various branches of economy; of trends in R&D expense pattern changes (increased share of expenditures on improving material and technical base of science) and research personnel skills (increased share of highly skilled researchers - doctors and candidates of science); of reduced rates of the total manpower growth. A forecast of resource supply changes was made by analysing and extrapolating the trends of indicator time series.

### *Utilization of results*

The above method and the collected information on R&D carried out in the branches of the national economy, provided a basis for a comprehensive analysis of sectoral scientific and technological problems and for the identification of the priority research tasks meeting different national economic goals. It became possible to study scientific and technological relationships between sectoral economic complexes, and identify inter-industry problems common to several complexes. A forecast of the likely development of scientific and technological potential and of resource allocation to R&D was prepared.

The method was used for the preparation of sectoral science development forecasts.

## 2.2 Forecasting and programme planning of medical research

### *Goals*

Health care of the people is one of the most important of socioeconomic objectives. Its solution is largely determined by advances in bio-medical science. In the USSR bio-medical research is carried out in numerous research institutions and higher educational establishments of different industries and organizations. So the management system of bio-medical science is of complex matrix structure. Hence, development of research policy in the health sector and the implementation thereof was considered as of vital importance.

The research policy manifests itself in identifying the most pressing development directions of medical science, and the priority problems whose solution will heavily contribute to the accomplishment of the standing goals. In pursuing a chosen policy, special attention should be given to the research efforts making the greatest contribution to the solution of crucial health care and medical problems. It is necessary to choose such research projects, to coordinate them, to promote their accomplishment, and to effectively apply the obtained results.

Coordination of efforts within the major research directions plays a special role as ministries and agencies allocate their resources to bio-medical research independently, and may have their own systems of goals far from always matching the national scientific and technological policy in bio-medical sciences.

Harmonization of different approaches and integration of efforts are exercised at the preparatory stage of forecast formulation, and while drawing up research programmes and plans. Forecasting and planning of bio-medical research require the solution of the following tasks:

- choice of pressing directions of research;
- priority analysis and determination of research problems;
- comprehensive analysis of the planned research and assessment of the accomplished results.

### *Approach employed*

The problem structure of bio-medical science can be represented as a multilevel hierarchical scheme comprising scientific research branches, problems and projects.

A branch of research (complex problem) is a large area of bio-medical science concerned with problems such as the protection and improvement of health of both individuals and society, perception of the essence of life phenomena, the causes and mechanisms of diseases, the development and improvement of methods and means of prophylaxis, diagnosis and treatment.

A problem is a relatively independent part of a research branch covering the basic theoretical, experimental, clinical, or socio-hygienic aspects of the given branch and containing explicit research objectives.

It is generally accepted to treat a research project as autonomous research. In 1988, there were over 40 branches and more than 200 problems in bio-medical science within the frameworks of which more than ten thousand projects were worked on annually.

The coordinating functions in the whole field were exercised by the Scientific Boards of the USSR Academy of Medical Sciences which supervised research activities conducted within a certain area of medicine, participated in the development of forecasts, programmes, plans, and made expert judgement on planned projects and obtained results. Membership of the Scientific Boards and their problem committees was made up of prominent medical scientists, leading professionals and executive personnel of health care centres.

Pressing directions of bio-medicine for the forthcoming future were determined by management bodies in cooperation with the Scientific Boards proceeding from the needs of practical health care and development perspectives of bio-medical science. The list of problems and branches of bio-medical research reflected the scientific and technological research policy in the health sector.

The urgency of a research branch and the priority of a problem are versatile notions that can be characterized by a set of criteria representing preferences of management bodies. The composition and contents of these criteria were agreed upon with the eminent specialists of the Presidium of the USSR Academy of Medical Sciences. Interviewing of experts for estimating the branches and problems (about 1,000 members of Scientific Boards and problem committees of the USSR Academy of Medical Sciences were interrogated) was carried out with special questionnaires. Experts usually estimated the problems falling within the area of their scientific interests and competence.

The multicriteria expert analysis of the planned research projects and of the obtained results was carried out while formulating the current research plans and assessing the results of their fulfillment. First, each project was examined, with regard to its *problematique*, at a respective problem committee and then by a skilled expert - a member of the problem committee. To facilitate and unify the above procedures, and to utilize computer technology in information processing, special information documents have been developed to be filled in for each project. All information about the project was integrated into three groups: organizational information, topical contents of research and criterial estimates. The characteristics of the research theme and results were chosen on the basis of systems analysis of medicine, and analysis of the informational needs of medical science management bodies.

### *Criteria*

The *research branches* have been estimated against four criteria.

H1. Contribution of the research branch to the solution of the major bio-medical problems.
H2. Contribution of the research branch to the solution of the major health sector problems.
H3. Feasibility of accomplishing radically new scientific results in the near future.
H4. Possibility of rapid implementation of the scientific results in health care.

The *problem estimation* criteria were chosen to be:

P1. Contribution of the problem to the solution of public health protection objectives.
P2. Fundamental significance of the problem.
P3. Applied significance of the problem.
P4. Prospectivity of the problem.
P5. Spin-off (impact of the problem solution on other problems).
P6. Comparative level of theoretical research into the problem in the USSR and abroad.
P7. Comparative level of experimental studies into the problem in the USSR and abroad.

The *planned research project* is estimated by the following criteria:

T1. Priority.
T2. Urgency.
T3. Prospectivity.
T4. Methodological level.
T5. Fundamental significance.
T6. Applied significance.

To estimate the *obtained results* use was made of the following criteria:

R1. Novelty.
R2. Theoretical utility.
R3. Practical utility.
R4. Expected benefits of utilization.

The research branch and problem assessment against each criterion was carried out on special quality scales which had expanded verbal descriptions. For example, criterion P1 had the following estimate scale:

P1. Contribution of the problem to the solution of public health protection objectives:

a. research conducted within the given problem makes a considerable contribution to the solution of a set of the major tasks concerned with public health protection aimed at reducing the general and occupational sickness rate, invalidity and mortality;
b. research conducted within the given problem makes a considerable contribution to the solution of individual major tasks of public health protection;
c. research conducted within the given problem does not make any meaningful contribution to the solution of the major health protection objectives.

### *Method*

The choice of pressing research branches and analysis of research problem priority boil down to ordering (ranking) the respective objects by the selected criteria. The interrogation of experts was carried out by two methods: paired comparison technique and multiattribute expert assessment.

The first of the above methods was used for identifying the most important directions of bio-medical science out of the compiled list of research directions. First, ranking was performed against the four partial criteria H1-H4. The analysis of correlation between the rankings by individual criteria made it possible to single out two of them - H1 and H2 - which most fully characterized the expert preferences. Non metric factorial analysis made it possible to combine partial criteria into an aggregate criterion which helped determine a central group of six directions considered most crucial.

The relative priority of problems was determined by both methods. The multiattribute expert assessment involved separate rankings against criteria P1-P5 followed by the final ordering on the basis of the vector preference relation. With a view to ranking the problems, which turned out to be incomparable, a special procedure was developed making use of decision-maker preferences.

The problem-rankings obtained by the two different techniques were sufficiently close in a considerable number of research branches. This made it possible to distinguish a set of priority problems The consistency of expert estimates was quite satisfactory. In addition, subgroups of highly consistent expert opinions was established, and the stability of final ordering with respect to the above procedure was checked. The multiple criteria problem estimates also permit identification of problems meeting certain estimates against individual criteria or combinations of estimates, and exercise an additional analysis of these problems.

A multiattribute assessment of a research project in launching and completing is performed through the expert review making no use of formal procedures. The expert recommends the incorporation of a project in the plan, following the acquaintance with its content reflecting the research objectives, the employed methods and equipment, and the expected results. Account is also taken of the project's feasibility, the available resources and the schedule. The contribution made by the project to the accomplishment of health care and medical science objectives is assessed by criteria T1-T6. In reviewing the results of research the expert, by making use of criteria P1-P4, estimates the obtained results, their correspondence with the plan targets, and makes recommendations on their application in medical practice.

### *Utilization of results*

The results of problem and branch priority analysis and their comparison with foreign levels were used by the Academy of Medical Sciences of the USSR in drawing up advanced research plans and formulation of bio-medical science development forecasts.

The multiattribute assessment of problems and projects was used in drawing up programmes, plans of research activities in medicine, and in analysing their accomplishments. The review of planned bio-medical projects and of obtained results was one of the compulsory phases in the ordered procedure of annual planning and accountability of bio-medical research.

## 2.3 Long-range programme planning of astronomical research

### *Goals*

The trends emerging in astronomical research in recent years are characteristic of the majority of areas of fundamental science: increasingly expanding range of research, and the sharply growing technical difficulties of accomplishing new scientific results. The successes in astronomical research are largely determined by the availability of unique, expensive and sophisticated equipment. The considered method was used for solving the following objectives in long-range planning of astronomical research:

- determination of astronomical observation facilities required for the solution of the assigned objectives;
- allocation of scarce resources to the manufacture and acquisition of technical facilities supporting the accomplishment of the research objectives;
- feasibility analysis of the task solution with the available technical base.

### *Approach employed*

The approach is based on modelling the relationships of goals, methods and tools of fundamental research. The general model structure is a hierarchical scheme where the research goals are treated as a progress in solving the research tasks in a concrete scientific area integrating a number of research branches. The combined ways to goal accomplishment are research tasks. The research methods and technical facilities are treated as tools for the goal achievement.

A branch of research in astronomy integrates a set of research problems involving the basic issues of the structure of the Universe and the evolution of its separate objects. A research problem boils down to the study into different parameters of a certain class of celestial objects by different techniques for solution of a scientific problem or part of it. The research method is a combination of technical observational facilities, observation techniques, and those of data processing. Technical facilities comprise telescopes, analysers, detectors, signal recording and processing systems and other auxiliary technical equipment.

The model covered 25 branches of research, 67 scientific problems, 56 research methods and 63 types of technical facilities. The lists of the components of all model levels were agreed upon with the Astronomical Board of the USSR Academy of Sciences, and prominent Soviet astronomers. The experts evaluating all the model's components were leading Soviet scientists representing all astronomical centres of the USSR. The experts were interviewed using special questionnaires.

### *Criteria*

For the estimation of *research branches* use was made of the following eleven criteria:

H1. Fundamental utility of the branch.
H2. Prospectivity of the branch.
H3. Applied utility of the branch.
H4. Possibility of rapid introduction of results into the national economy.
H5. Contribution of the USSR Academy of Sciences to the research conducted within the branch.
H6. Trends in the changes of the Academy's role.
H7. Adequacy of branch staffing.
H8. The level of observation organization in the branch.
H9. Availability of foreign observational data in the branch
H10. The level of theoretical research in the USSR.
H11. The level of astronomical research in the USSR.

The *research tasks* were assessed against the following seven criteria:

P1. Contribution of the task to the solution of the major astronomical problems.
P2. Prospectivity of different types of observation within the context of the task.
P3. Comparison of national and foreign levels of theoretical research into the problem.
P4. Comparison of national and foreign levels of astronomical observations within the context of the problem.
P5. The level of task staffing.
P6. The level of observation arrangement within the context of the problem.
P7. Availability of foreign observation data on the problem.

The efficiency of *research methods* was evaluated against three criteria:

M1. The utilization of different research methods into the given problem.
M2. Informativeness of different observational methods as applied to objects of the given task.
M3. Versatility of the results obtained by different methods within the context of the given task.

The evaluation of *technical facilities* was conducted against seven criteria:

T1. Efficiency of the variety of research techniques and telescopes employed in the USSR.
T2. Comparative efficiency of Soviet and foreign research techniques as applied to one and the same telescope.
T3. Impact of the telescope quality and type on efficiency of the employed methods.
T4. The task's demand for different types of telescopes.
T5. The research task's demand for telescopes of different sizes.
T6. Comparison of national and foreign samples of astronomical facilities.
T7. Comparison of experimental national and foreign samples of devices.

Scales with quantitative estimates were developed for all criteria. For example, a scale for criterion H1 looked like:

H1. Fundamental utility of the branch.

a. the results generated within the branch make a significant contribution in solving global scientific objectives of astronomy and considerably bear upon the future development of astronomy as a whole;
b. the results obtained within the given branch are, undoubtedly, important and necessary for accomplishing some global astronomical problems;
c. the results obtained within the given branch will enhance solution of some global astronomical problems;
d. progress in the solution of global astronomical problems has nothing to do with (does not depend on) the level of research within the context of the given branch.

### *Method*

The basic procedure of the method is a sequential transition from research objectives to technical facilities when allocating resources (downward transition) or from technical facilities to goals when analysing capacities of devices (upward transition).

The research goals (policy) were formulated by the management body or decision-maker against a set of the branch assessment criteria in the form of a combination of some estimates. Thus, for example, a research policy alternative requiring to focus, in the near future, on the research branches which are of fundamental significance, promising from the standpoint of possible scientific results, and indirectly affect solution of national economic problems may be represented as a set of estimates by criteria H1 a,b - H2 a,b - H3 a,b,c. Each policy alternative is put in correspondence with a certain subset of branches meeting the prescribed set of estimates.

The choice of a subset of research branches is followed by identification of problems in which the research will make the greatest contribution to the progress toward the goals established by the scientific research policy. The tasks are selected depending on their contribution to meeting the major astronomical objectives (criterion P1) and a set of estimates characterizing different aspects of the task (criteria P3-P7).The tasks heavily contributing to the solution of at least one of the chosen problems and having an estimate by criterion P1 not worse than the prescribed one (the estimate was done by the decision-maker), are selected irrespective of their estimates by the remaining criteria. The task whose estimates against criterion P1 are worse than the prescribed ones are analysed additionally for the correspondence with the combination of requirements by criteria P3-P7.

The choice of research methods is carried out with respect to each of the selected research tasks since the effectiveness of one and the same method is dissimilar within the context of different problems. The procedure of method selection was developed in cooperation with the manager and took account of his preferences. A set of problems, selected at the preceding stage, is initially divided into three groups depending on the estimates by criterion P2 characterizing the specifics of the present state and development prospects of the considered problems. Criteria M2 and M3 set different requirements to the methods as applied to the problems of each identified group.

The following stage was devoted to the identification of technical facilities whose absence or characteristics do not allow one to take advantage of the methods' capacities in studying the objects within the chosen research tasks. The procedure for identifying the list of scarce technical facilities was compiled in close collaboration with decision-makers. This procedure involved the analysis of the impact which the parameters of serial and experimental domestic devices have on the capabilities of the methods, and the comparison of domestically built equipment with the best analogous foreign types (the characteristics of telescopes, and auxiliary equipment were reviewed separately).

Following completion of the foregoing stages of the method, the lists of telescopes necessary for accomplishing the research goals were compiled accompanied by evaluation of the degree of their scarcity. Also, a list of scarce auxiliary equipment was drawn up specifying critical parameters for serial and experimental prototypes.

### *Utilization of results*

The definition of technical facilities required for the accomplishment of the assigned research goals provides a basis for the formulation of finance plan options for astronomical research, thus making it possible, to some extent, to ease the shortage of technical facilities. The shortage can possibly be alleviated by the importation of foreign and the purchase of domestic equipment with the required characteristics or by organization of the production of necessary technical facilities.

The selection of ways to alleviating the shortage accompanies the preparation of funding plan alternatives with regard to monetary and production constraints. An alternative plan is considered feasible if the shortage of technical facilities can be eliminated without exceeding the present constraints on all kinds of resources. In case no plan alternative is practicable, it is necessary to adjust the research policy by way of increasing the requirements to the assessment of problems and research branches.

In a general case, the choice of an acceptable alternative of resource allocation is an iterative procedure where each step involves an adjustment of the initial research policy alternative and an evaluation of consequences of this adjustment. Analysing an influence of the changing requirements against criteria on the final result, the decision-maker can identify the "most critical" components and criteria; and change, if necessary, the list of criteria and relationships between the model's components. This procedure is reiterated, with decision-maker participation, until all assigned resource constraints are met, or the decision-maker is sure that the available resources do not allow the accomplishment of the research goals. In this case decision-maker may change resource constraints.

When the resource allocation alternative is known from the outset (i.e. there is a plan of equipment purchase or a concrete technical base of research) the research branches, where maximum progress can be made, are determined in a similar manner. In a sense, this problem is the reverse of the preceding one, and in order to solve it, it is necessary to go up through the hierarchical scheme.

This method was used by the Astronomical Board of the USSR Academy of Sciences for elaboration of observation programmes in a number of astrophysical observatories of the Academy.

## 2.4 Elaboration of an interdisciplinary programme:"Surface"

### *Goals*

One of the key objectives of material science is to study the structure and properties of materials' surface and surface phenomena. The study of the surface is an essentially interdisciplinary problem worked on by many research institutions in physics, chemistry, engineering and other disciplines. The outcome of this research is very important for meeting the demand of the national economy for materials with specified properties. At the same time, research into surface processes was characterized by the lack of explicit coordination of efforts, by insufficiently effective utilization of available equipment. All this made it necessary to set up an interdisciplinary programme, entitled "Surface", behind which was a deep and comprehensive analysis of different aspects of research and its resource supply.

The following tasks have been solved with respect to the interdisciplinary "Surface" field:

- analysis of the fundamental research contribution to solving practical national economic problems;
- identification of the perspective areas of fundamental research in urgent need of additional equipment, and

determination of a set of practical tasks whose solution may benefit from the identified fundamental research;
- analysis of the specified set of applied problems (identification of a set of fundamental problems associated with the specified applied ones, and a list of Institutes conducting research in the above areas).

### *Approach employed*

A key stage in the "Surface" programme elaboration is the development of a logical model having a multilevel hierarchical structure and reflecting the relationships between the programme components. The basic blocks of the model are: fundamental research, applied research, practical problems, and resource requirements for programme accomplishment. Each block of the model is disaggregated into components, and the degree of detail was determined by the specifics of the block and by the nature of the possible relationships with the components of other blocks.

Fundamental and applied research are treated according to standard definitions. The majority of them are of complex, interdisciplinary nature and cannot be easily referred to the established fields of science. Composition of the "fundamental research" block was determined by analysing the plans of research activities at the Institutes of the USSR Academy of Sciences with the assistance of experts who were leading specialists in the respective areas of research. The effort resulted in the identification of 33 fundamental problems.

Applied research is oriented toward the solution of practical problems. The "applied research" block comprises 75 applied problems. Its components were chosen on the basis of data available at the USSR Academy of Sciences concerning the introduction of research results in practice with regard to the major R&D trends in the field of materials science abroad.

The "practical problems" cover the basic needs of different branches of the national economy in new materials and manufacturing processes. Altogether, the block contains 40 most important practical problems categorized as several groups. The practical problems were formulated and put together on the basis of an analysis of up to date plans of activities in different branches of the national economy.

The "resource" block is concerned with research personnel and technical facilities available at the Institutes of the USSR Academy of Sciences and Academies of Sciences of republics conducting research into different surface phenomena.

Construction and evaluation of the model components were carried out with the assistance of the leading experts in surface research working in different fields of science. The list of experts was compiled with the assistance of the USSR Academy of Sciences' Presidium. The experts acquainted themselves with the general aims of the inquiry in advance. They selected, out of a variety of model components, the ones that lay within the range of their professional interests. Then the components of all blocks and relationships between fundamental and applied research, applied research and practical problems were evaluated by a special procedure. With a view to evaluating the model's components and relations between them, quantitative criteria were formulated.

### *Criteria*

The fundamental problems were evaluated against three criteria:

F1. The level of fundamental research in the USSR and abroad.

F2. Prospects for fundamental research.

F3. Resource requirements.

For evaluating the relations between the model's components use was made of the following criteria:

B1. Contribution of fundamental research output to solving applied problems.

B2. Contribution of applied research to the solution of practical problems.

Scales with expanded verbal estimates reflecting quality divisions and distinguishable for decision-makers and experts were developed for all criteria.

### *Method*

The development of alternative decisions and analysis of their implications were assisted by the Programme Committee and boiled down to select various subsets of components of each model block which met certain requirements.

The analysis of the contribution of fundamental research to the solving of practical problems was performed as follows. First, a list of practical problems was specified, followed by determination of a subset of applied problems of the greatest significance for the solution of the practical problems. Included in the subset were the applied problems having the best estimates against the criterion of contribution to solving the specified practical problems (criterion B2). Then fundamental problems were chosen whose results decisively contribute to solving a subset of applied problems specified earlier, i.e. fundamental problems having the best estimate by criterion Bl with respect to at least one of the identified applied problems. It was found that three fundamental problems have principal significance for solving the overwhelming majority of practical problems. The thus formulated subsets of fundamental problems was behind the list of Institutes conducting the key research into these problems.

Solution of the second problem was carried out in reverse order. First, identified out of the variety of fundamental problems were ones having the necessary combination of estimates against criteria, i.e. the most perspective problems (the highest estimates by criterion F2) whose level of research corresponds to foreign standards or somewhat lags behind (the lowest estimates by criterion F1) but for which the allocation of additional resources would considerably improve the state of affairs (the highest estimates by criterion F3). Then analysis was made of the contribution of the identified fundamental problems to the solution of applied problems, which makes it possible to select those applied problems whose solution is especially affected by the identified fundamental problems (the highest estimates by criterion B1). Then, identified in a similar way are the practical problems whose solution is related to the identified applied problems, and the significance of fundamental problems for each practical problem is assessed.

Only four out of a variety of fundamental problems had the necessary combination of estimates by criteria. The analysis of the contribution of the applied problems, identified for each of the earlier selected fundamental problems, to the solution of practical problems revealed their significance for a considerable part of the problems at hand. The final stage is concerned with the compilation of a list of Institutes conducting the respective fundamental research and which are in need of additional resources for enhancing the research and speeding up solution of the problems faced.

The analysis of the assigned set of applied problems involves determination of the associated subset of fundamental problems and practical problems. Nine applied problems in which some ministries, funding the research into material surface phenomena, showed interest, were chosen as an original subset. It was determined that the solution of the above problems required research into eight fundamental problems, two out of which are especially important for all identified problems. This information provided a basis for a list of Institutes working in the mentioned areas. Also mentioned are the practical problems whose solution is associated with the research into the chosen applied problems.

### *Utilization of results*

Application of the method followed a comprehensive analysis of the current state-of-the-art and trends in research relating to various aspects of the study of materials' surface. It also helped determine relations between fundamental and applied problems, and define the contribution of possible results of research in the solution of national economic objectives. The developed model makes it possible to formulate and structure scientific and technological policy alternatives, to identify and analyse the deterrent and supporting factors affecting the solution of practical problems, and to obtain information necessary for the allocation of additional resources to the Institutes conducting the respective fundamental research.

The method was used for the elaboration of an interdisciplinary research programme entitled "Surface" at the USSR Academy of Sciences.

## 2.5 Assessment of research and experimental development requests

### *Goals*

The problem of choice of R&D branches and projects has been gaining an ever-increasing significance for the implementation of scientific and technological policy in recent decades. The range and cost of research activities are increasing. When the scope of R&D exceeds the available resources, the management body faces the need to exercise a deep and comprehensive evaluation of activities and to select the most significant ones to be included in the plan.

The same problem faces the leadership of ministries and agencies when evaluating the incoming requests for R&D. The choice of some alternative R&D is affected both by quantitative factors (cost, benefit, etc.) and qualitative factors (availability of scientific back-log, skills of would-be performers, etc.) and the latter usually prevail over the quantitative factors.

For the solution of ill-structured problems of alternative evaluation and choice under multiple criteria use was made of the ZAPROS method (see Annex 1). This helped to perform the following tasks:

- the multiattribute evaluation of R&D requests;
- the drawing up of R&D plans (programmes).

### *Approach employed*

In the first place, a list of R&D requests and a system of criteria for their evaluation were developed. The criteria reflect the scientific and technological policy pursued by the management body or a decision-maker. Therefore, in constructing a set of criteria account should be taken of all essential criteria. The completeness of this system is checked by a logical analysis with the decision-maker's participation.

The key problem here is to elicit correct R&D request estimates from experts. For this purpose, use was made of qualitative criterion estimate scales with a small number of divisions. The estimates against each criterion were formulated in cooperation with the decision-maker. Their quantity was determined by the latter who wanted to differentiate certain distinguishable levels to be measured. Each estimate formulation was discussed in detail with a group of potential experts. Special procedures of expert interviews and expert information processing, accounting for its qualitative character, were developed.

A model of general utility for R&D requests usually breaks the entire variety of estimate combinations into ordered subsets. Each R&D request which was assigned a certain combination of criteria estimates is put in some prescribed utility class. A decision rule is constructed on the basis of information elicited from the decision-maker concerning his preferences reflecting the scientific and technological policy of the management body.

### *Criteria*

For evaluating R&D requests use was made of seven criteria:

K1. Scale of the activity (practical utility of results for solving major technological problems or objectives);

K2. Contribution to the development of new, and improvement of the available, technology.

K3. Expected results.

K4. Validity of the R&D request.

K5. Versatility of results (possibility of the results employment in different branches of the national economy).

K6. Comparative characteristics of the activities with foreign data on similar R&D.

K7. Readiness of the potential designers for project implementation.

All criteria scales were given expanded estimate formulations. Thus, for criterion K3, they were described as follows:

K3. Expected results:

a. the results will be in the form of operating prototypes of make-ups;
b. the results will be in the form of report with conclusions and concrete recommendations on their utilization;
c. the results will be in the form of report indicating the extent of their feasibility or infeasibility.

### *Method*

First of all, R&D requests coming to the planning body are divided into groups of activities close to the topics. Each topical group is assigned to experts exercising a multiattribute assessment of the requests. Each request is first assessed by one expert and then subjected to estimation by some other more authoritative expert.

The step-by-step interrogation of the decision-maker identifies his preferences, making it possible to formulate a decision rule according to which the entire variety of criterion estimate combinations is categorized as best, intermediate, and worst estimate combinations with respect to utility. The combination of the best (top) estimates by all criteria forms a natural subset of the best estimates, the combination of the worst (lower) estimates forms a subset of the worst estimates. Corresponding to each subset of combinations of criterion estimates is a certain class of request values.

On passing the expert analysis procedure, the R&D requests are assigned, by the aggregate of partial estimates, a general estimate of their value according to which the activities are either included in the plan (programme) straight away, or put in reserve, or rejected. Since the requests arrive and are being evaluated during the entire period of plan formulation, the final decision on the plan format may require an adjustment of the original decision rule with regard to the concrete requests' estimates.

So, the employed approach makes it possible to elicit information from experts and decision-makers, verify it, classify the requests, and rank the groups by their significance for implementing scientific and technological policy of the management body. Note that at all stages of the method the information obtained from experts and decision-makers is processed without distortion.

### *Utilization of results*

The method was successfully used in R&D planning at the USSR Academy of Sciences. They have developed and run on the computer special man-machine procedures of information collection and processing of all incoming requests, allowing a quick and prompt preparation of recommendations for the planning bodies, and made it possible to draw their attention to R&D projects that did not meet the necessary requirements.

## 2.6 Programme planning of applied research and experimental development with regard to resource constraints

### *Goals*

In planning applied research and experimental development the planning body, pursuing own certain scientific and technological policy, faces the need to select certain R&D projects to be financed, and to argue the final option of the plan with the superior authorities.

The number of projects is rather considerable, and they are complicated and diverse. The resources required for implementing each project are comparable with one another and insignificant as compared with the amount of resources available at the planning body's disposal. The total volume of required resources, however, exceeds that available. Hence, it is necessary to choose the most preferable projects consistent with the scientific and technological policy of the planning body and securing the greatest possible economic effect.

The major tasks, solved by the method of planning under resource constraints, are:

- definition of project alternatives with regard to resource constraints;
- choice of a valid alternative plan.

### *Approach employed*

A scientific and technological policy of the planning body, which consists of individuals unanimous with respect to the pursued policy or reports to one and the same decision-maker, is drawn up in the form of two sets of qualitative and economic criteria. These criteria must reflect all factors which the planning body takes into account in considering the projects. Bids for development come from a reporting or superior organization, or from an external organization. To some extent, the projects are supported with manpower and material resources.

There is an opportunity for inviting experts who may skilfully and unbiasedly review and evaluate each R&D project separately, given explicitly stated criteria. The experts may offer different options of project implementation. Each R&D project can be implemented in different ways: by the given research organization alone, through international scientific and technological cooperation, or purchase of foreign licences, technologies, etc. Options differ in expenses of different currencies lead time, required material and manpower resources, etc.

Feasibility of each project is determined by the availability of skilled personnel, and financial and material resources (necessary equipment, materials, etc.). The statement of the considered task assumes that, during some time if necessary (time is determined by the experts) the required manpower can be trained abroad or at home, and the lacking materials bought abroad, given sufficient financial resources in national and foreign currencies.

In conformity with the policy of the planning body the entire variety of R&D projects is broken into two classes: projects of prime significance performed in the first place, and ordinary projects whose implementation depends on the expected economic benefits. The project financing plan accounts for the significance of each R&D project, different implementation alternatives, and the expected economic effect. The constraints imposed on the plan boil down to time limits and monetary constraints. The latter are imposed for each financing period, say, each year.

### *Criteria*

The scientific and technological policy of the planning body is presented by the following criteria:

P1. Correspondence of the considered R&D project with the prospects for scientific and technological progress of the country.
P2. Project orientation (scale of utilizing the expected results).
P3. Direct impact of the expected results on solution of the major national economic problems.
P4. Political significance of the considered R&D project.
P5. Correspondence of the R&D project with the obligations to CMEA or bilateral contracts.
P6. Correspondence of the expected results with the level elsewhere in the world.
P7. Novelty of the problem being solved.
P8. Characteristics of the R&D project's contributors.

*Resource-expenditure* criteria are used as economic criteria:

E1. Expected monetary expenses per year.
E2. Expected currency expenditure (socialist and convertible currencies).
E3. Number and skills of the necessary but unavailable specialists.
E4. Total duration of the project.
E5. Expected economic effect.

Criteria of an economic character have *quantitative* estimate scales. For *qualitative* criteria ordinal scales were developed with a small number of divisions and extended verbal descriptions. For example, for criterion P6 the scale looks like this:

P6. Correspondence of the expected results with the level elsewhere in the world:

a. the expected results are superior to the world level;
b. the expected results correspond to the world level;
c. the expected results are inferior to the world level.

### *Method*

The evaluation of the significance of R&D projects and the identification of priority projects are carried out with the assistance of the planning body management on the basis of the developed set of criteria. Naturally, the projects having the highest estimates against all qualitative criteria belong to a class of projects of prime significance, and those with the lowest estimates belong to a class of ordinary projects. There is an area of uncertainty between the two extremes comprising projects with different sets of estimates. This must be narrowed to a clear interface dividing all the projects into two classes.

For performing this task use is made of man-machine direct classification method CLASS (see Annex 2) where a basic idea is as follows. The decision-maker is presented combinations of estimates by all criteria. The information elicited from the decision-maker is extended to a number of other combinations, on the basis of dominance relations (use is made of the rank relations on criteria scales). The decision-maker's answers are checked for consistency and any detected contradictions removed. Then feasible project implementation alternatives are determined with the help of experts (up to 12 different types of alternatives).

The acquired information is used as a basis for formulation of the project financing plan, which must provide:

- mandatory incorporation in the plan of every R&D project of prime significance;

- selection of a set of R&D projects securing the greatest possible aggregate economic effect given a rational consumption of the available resources.

From the mathematical standpoint the considered problem is a discrete programming problem that can be referred to as a problem of packing "multidimensional knapsacks". The heuristic algorithm for solving the given problem is based on the idea of successive packing of "numerous knapsacks". First, all projects of prime significance are packed. Then, ordinary projects with the highest values of economic effect are added. On approaching constraints, the alternatives of prime significance projects are excluded in a certain order (given a mandatory preservation of an alternative of each project of this class).

### *Utilization of results*

The method was employed in drawing up R&D plans in two State-owned economic associations in Bulgaria. About 240 projects with different implementation alternatives were reviewed and evaluated. Special man-machine procedures of information collection and processing were developed and run on the computer with a view to assessing the R&D projects and financing plan. The method made it possible to develop project finance plans meeting the aggregate requirements of participants in the process of planning.

# Annex 1

# The ZAPROS method

The ZAPROS (Closed Procedures By Reference Situations) method is designed for ranking multiattribute alternatives on the basis of decision-maker preferences. The basic elements of the method are:

- determination of a set of criteria and construction of ordinal scales of estimates by each criterion reflecting, in verbal form, all essential aspects of the considered problem;
- decision-maker interrogation with a view to identifying his preferences and building a decision rule for ranking the multiattribute alternatives;
- interviewing the experts to elicite a multicriteria project estimate and order the groups of projects.

Criteria $K_i$ (i=1,...,n) and estimate scales $K_{ij}$ (j=1,...,$m_i$) used for problem description constitute a decision model. The ZAPROS method employs a verbal description of the estimate scales which is a convenient and customary language of interaction between decision-maker and expert. This improves the credibility of the information elicited from the experts and the degree of confidence on the part of the decision-maker.

A set of criteria $\{K_i\}$ and the statements of criteria values $\{K_{ij}\}$ reflect, in a structured form, the decision-maker's policy. The estimate scale descriptions, which can be both concise and extended, make it possible to take account of uncertainties associated with the inadequate knowledge of decision implications, and a risk related with certain alternatives. It is assumed that quality grades are ordered from the best to the worst value (ordinal scales).

A decision-making rule reflecting the preferences of the decision-maker is built by a special procedure of decision-maker interrogation during which a pairwise comparison of multicriteria vectors (alternatives), constituting a set of estimate combinations by all criteria $A = \{K_{1p}, K_{2q}, \ldots, K_{nr}\}$ takes place. Questions to the decision-maker are in the form of verbal statements close to natural language.

Each combination of criteria estimates is an image of some object possessing the respective properties. The most contrasting are the so-called "reference situations" $A_b$ and $A_w$, corresponding to the combinations of the best and the worst estimates against all criteria:

$$A_b = \{K_{11},\ K_{21}, \ldots, K_{n1}\}$$
$$A_w = \{K_{1m1},\ K_{2m2}, \ldots, K_{nmn}\}$$

The decision-maker performs a pairwise comparison of alternatives (evaluates quality variations against all pairs of criteria) starting the procedure once with the best-, and the other time with the worst- reference situation. A closed procedure evolves which makes it possible to check decision-maker's preferences for consistency and transitivity. The pairwise comparisons provide ground for a unified ordinal scale of estimates by all criteria. Note that as the number of criteria n grows, the abundance of information required for the construction of a unified scale increases.

On the basis of the unified estimate scale and with regard to criteria mutual dependence or independence, they build a decision rule breaking the entire set of alternatives into ordered classes of the best-, intermediate-, or worst-quality alternatives.

Ordering of real objects is carried out by the available decision rule. Experts estimate the objects against the formulated criteria reflecting the decision-maker's policy. The multicriteria assessment of an object attributes it to one of the identified classes of alternatives ranked with respect to quality Note that throughout the ZAPROS procedure, the descriptive information is not subject to any transformation or distortion.

### *Fields of application*

ZAPROS is used for the assessment and choice of research and experimental development projects. In R&D programming the method is suitable for building up a "portfolio" of projects, i.e. evaluating the bids and ranking them with respect to expediency of their incorporation in the overall plan. The method is also helpful in assessing project priorities. The reasonable range of method application is as follows: the number of criteria, n = 2-9; the number of scale divisions, m = 2-6; the number of evaluated objects — from several score to several hundred.

### *Advantages and disadvantages*

The method has some advantages. In the course of interviewing the decision-maker compares only a small number of multicriteria alternatives differing in estimates by just two criteria, and having the rest of the estimates that belong to reference situations. It is possible to identify errors and inconsistencies in the decision-maker's responses, and to analyse and correct them on the basis of information elicited from the decision-maker.

The procedure of building a decision rule involves checking the implementation of the axiom on a pairwise independence of criteria with respect to preferences by presenting analogous pairs of alternatives near the two reference situations. Given the criteria independence it is possible to construct a unified ordinal scale of alternatives' estimates. Given the criteria dependence, a unified ordinal scale is built only for a respective subset of the pairwise independent criteria. The remaining alternatives are compared only with respect to dominance.

Since the decision-maker compares, generally speaking, hypothetical alternatives, the information elicited from him does not guarantee the connectedness of the final quasiordering. Therefore, the system envisages an opportunity for determining the alternative ranks by different principles (identification of non-dominated alternatives, identification of non-dominating alternatives, by the maximum of dominated, and by the maximum of dominating alternatives).

The method is complex, and the complexity sharply increases as the number of criteria and scale divisions increase. Identification of decision-maker's preferences, the construction of the decision rule, and the processing of expert information are carried out by special procedures and algorithms. The use of the computer is highly desirable.

# Annex 2

# The CLASS method

The method of direct classification CLASS is helpful for solving problems where it is necessary to put multiattribute objects (decision alternatives) into different classes. These objects can typically be described in terms of their properties which are treated as criterion estimates characterizing objects. The method is based on expert or decision-maker's knowledge and involves the following principal stages:

- structuring a problem area and identifying object characteristics against criteria with ordinal or nominal scales;
- interviewing the expert or decision-maker to elicit knowledge and to construct a complete and consistent knowledge base containing decision classification rules.

Criteria $K_i$ (i=1,...,n) are characterized by the main features (properties) of classified objects. In the CLASS method most often the estimate scale $K_{ij}$ (j=1,...,$m_i$) is an ordinal one with a small number of values. To represent the objects, it is convenient to use verbal descriptions of qualitative values and resort to quantitative scales only where these are natural. The order of values for the criterion scales depends on the purpose of problem solving: the order may reflect the quality of the object (ordering them from the best to the worst) or the degree to which the criterion values are characteristic of the respective class of decisions (ordering them from the most characteristic to the least characteristic one).

### *Classification*

An arbitrary combination of criterion estimates (multidimensional vector) $A = \{K_{1p}, K_{2p}, \ldots, K_{nr}\}$ is assigned to a hypothetical object. The objects for which similar decisions have been made are brought together in classes. The expert's task is to specify a set of possible decision classes for each object or, in other words, to formulate a complete decision classification rule. There are N decision classes in the general case. So for real problems it is clear that the expert would simply not be able to classify all objects because there are hundreds of thousands of real alternatives. The problems handled by CLASS involve objects characterized by ordinal criterion scales and ordered classes of decisions. Under these conditions, it is possible to construct a classification of relatively small vector estimates and, making use of information elicited from the expert, to classify the other vector estimates adequately.

Classification of objects follows the rational procedure of eliciting knowledge from the expert. The procedure consists of successive presentation of the most informative object (vector estimate) to the expert. The informativeness of the object is determined by a measure of the object proximity to a certain decision class that depends on the probability of assigning the object to this class. After the expert has assigned the vector estimate to some class, the remaining non-defined objects are again subjected to a calculation of the measure of informativeness, and the process is repeated. The suggested interrogation procedure of knowledge elicitation generates the object classification with a relatively small number of questions to the expert.

No interrogation procedure is immune to erroneous responses. There can be both random errors and errors associated with inconsistencies in the preferences of the expert. So a special procedure of searching for contradictory responses is included in CLASS. The task is to check the object classification for inconsistencies and to determine which objects should be presented to expert for repeat evaluation. It is necessary to select objects which would eliminate the inconsistency if they were transferred to another class. The information collected from the expert in this way may be efficiently arranged in the complete and consistent knowledge base.

### *Fields of application*

The CLASS method is applied to a wide variety of problems such as the evaluation and programme planning of R&D projects, medical and technical diagnostics, the evaluation of designs of industrial facilities, and so on. For example, with respect to the programme-planning of R&D projects a decision-maker may consider the following alternatives: definitely include the project in the plan, leave the project for further discussion, or definitely do not include the project in the plan. R&D projects can be characterized by criteria such as the skills of the researcher, significance, prospectivity, expected efficiency, cost, etc. Reliable information from the decision-maker or expert may be elicited when the number of criteria n = 2-9; the number of estimates on ordinal scales, m = 2-4; and the number of decision classes N = 2-5.

### *Advantages and disadvantages*

The method is based on an analysis of the capacity of the human information processing system and has the following distinguishing characteristics. It allows decision-makers and experts to obtain information they are accustomed to use in their native language. No techniques for obtaining unreliable information on subjective probabilities, scores, weights, values of membership functions, etc., are used. As a consequence the reliability of the information elicited increases.

The method generates a complete decision rule which makes it possible to define the decision class for any object. In addition, the search for informative question reduces the interrogation of the expert by a factor of 10-30. The method helps to test information for consistency, and to find and eliminate contradictions. It also calls for special training on the part of the decision-maker and expert.

CLASS is the comprehensive technique. Construction of the expert knowledge base, determination of the most informative questions, search for and removal of contradictions in expert preferences can be done only through interaction with the computer, making use of special procedures and algorithms. But when the knowledge base has been built the decision classification rule may be presented in a compact form convenient for application.

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