# Systems Analysis and Policy Planning: Applications in Defense

*Edited by E. S. Quade and W. I. Boucher*

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# Systems Analysis and Policy Planning

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## APPLICATIONS IN DEFENSE

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# PREFACE

"One of the key problems of contemporary national security policy," as Henry Kissinger has said, "is the ever-widening gap that has opened up between the sophistication of technical studies and the capacity of an already overworked leadership group to absorb their intricacy." This book, a survey of the nature, aims, and limitations of systems analysis in current defense planning, is an attempt to help close that gap. We focus on systems analysis because it is unquestionably the most powerful and widely influential approach to systematic inquiry that decisionmakers and policy-oriented analysts have at their disposal today – and are likely to have in the foreseeable future. We focus on its applications to problems of national security because here, in its traditional domain, there is a continuing and probably growing need, as Kissinger suggests, to understand the concepts and procedures of analysis. Almost daily, of course, there are new indications that systems analysis is beginning to discover a role in policy planning outside the area of defense, on all levels of government, in industry and commerce, and elsewhere. For this effort to be successful, however, we feel that it is essential to understand how systems analysis has worked in defense, and why. Here, too, in the search for new applications, this book may make a contribution, perhaps in helping to keep a possible gap from opening.

As a pioneer in the development of systems analysis and the techniques on which it relies, The RAND Corporation has long recognized the need to clarify the nature of analysis in defense planning. To this end, some twelve years ago RAND first began to offer short courses on systems analysis to senior military officers and civilians associated with the Armed Forces. To bring this material to a wider audience, the lectures given in 1959, much revised and amplified, were declassified and published in the open literature.* The most recent course, which was held in 1965, provided the basis for the present volume. Needless to say, those lectures given in 1965 that are retained in this volume have been thoroughly updated for publication at this time; indeed, most of them have also been enlarged or extensively revised. In addition, several new chapters have been written especially for this book. The resulting collection, we believe, extends the discussion of systems analysis in certain fundamental ways:

It makes an effort to account for the development of analysis in the last decade;

It discusses at length certain methods of analysis that either are receiving great emphasis today (such as a Monte Carlo computer

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*E. S. Quade (ed.), *Analysis for Military Decisions*, Rand McNally & Company, Chicago, 1964.

routine that simulates the operations and maintenance requirements of complex equipment at one or several locations) or are relatively new (such as the analytic scenario and the Delphi technique);

It attempts to anticipate the problems that analysts will have to overcome in the future, and to explore the reasons why these problems will arise;

And it reexamines earlier conclusions, particularly in the areas of establishing criteria for decisionmaking, weighing the utility of accepted standards for measuring the effectiveness of alternatives, defining the principles of suboptimization, handling the problem of uncertainty, and responding to the interaction between the pace of technological advance and the proper role and character of analysis itself.

This volume, like its predecessor, attempts to demonstrate that systems analysis can and does provide knowledge that decisionmakers need; that it can serve to sharpen intuition; that its usefulness is not limited solely to questions of policy and planning that can be quantified; and, most important, that whatever its weaknesses, it produces more fruitful results, of far greater consequence and reliability, than any of its alternatives. We should emphasize, however, that this book, while concerned with such essentials, is not simply introductory. It is intended more as a sophisticated guide to users of analysis than as a manual for those who prepare such material.

Its basic aim is to provide detailed answers – both practical and theoretical – to the questions that will be important to those responsible for sponsoring, evaluating, or implementing the analyses of others. What is systems analysis? Why is it necessary? When and where is it appropriate? How does one approach, and carry out, a systems analysis? What methods can be used? How can a good analysis be recognized? What can one expect from a systems analysis? How has analysis changed over the years? Why? What changes can be expected in the future?

The organization and contents of the whole reflect this emphasis on satisfying the needs of the *users* of systems analysis. The first six chapters explore the basic concepts of systems analysis. Included are an introductory example of analysis; a discussion of the problem of selecting operationally useful objectives, measures of their attainment, and criteria; a somewhat mathematical discussion of uncertainty; and an examination of the place and function of technological considerations in analyzing the merits of proposed systems. The next three chapters discuss the character and importance of costs in systems analysis. Resource analysis and cost-sensitivity analysis are illustrated in depth. The following nine chapters concern models – what they are, how they are constructed and used, what their limitations are, and what place they have in analysis as a whole. It is here that game theory, simulation, scenarios, war gaming, and political analysis are considered, as well as some newer techniques that attempt to provide a framework for obtaining the judgments of experts on problems that are not amenable to any of the methods of quantitative analysis.

Of the remaining four chapters, the first discusses a large variety of flaws, in both analysis and analysts, that can seriously affect the conduct or evaluation of systems studies. The second examines the character of analysis in the recent past, compares it to that of the present, and looks briefly ahead. The third returns to the opening example of analysis and shows, in light of what has gone between, how the problem might better have been approached and solved. The final chapter attempts to draw together the threads essential to the earlier discussions and, again, to take a look ahead.

Nowhere does this book presume an advanced knowledge of such specific tools of analysis as linear programming or probability theory, or their special applications to military problems.

In assembling this volume, we have made no attempt to eliminate the informality of the chapters that originally were lectures; nor have we attempted to impose a common viewpoint on the book as a whole. The authors remain their own agents, and each – it will be noted – takes a critical approach to his own topic, and that of the others. As editors, what we have tried to do is to give the book a unity, and at the same time discourage more than that minimum of repetition that would allow each chapter to stand by itself should the reader choose to revise our ordering. If we have succeeded, our greatest debt is to the authors themselves. But we also owe a good share of the credit to the assistance of our colleagues – in particular, R. L. Belzer, G. H. Clement, E. T. Lowe, and Col. J. W. Shinners (USAF), who helped us in selecting the topics and lecturers for the original seminar and provided critical comment.

This book and the course from which it derives were undertaken by The RAND Corporation as a part of its research program for the United States Air Force.

E.S.Q.
W.I.B.

*Santa Monica, California*
*December, 1967*

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## Chapter 1

# INTRODUCTION

### E. S. QUADE

*This chapter provides a preliminary view of the most general features of systems analysis. It describes the origins and scope of systems analysis; gives an idea of its nature; suggests where, why, and how it is helpful; and contrasts it with other forms of analysis. It also discusses the objectives of the other chapters in this book and how they are intended to contribute to the whole.*

## INTRODUCTORY REMARKS

Since 1961, the United States has introduced a new philosophy, technique, and style of defense management. To some extent this was inevitable; military planning today presents a new problem, different from earlier military planning, not in any deep logical or philosophical sense, but in a practical sense. The radical change in weapons, with their almost exponential increase in complexity, and the concomitant need for research and development, forced a new emphasis on science and engineering and rendered past military experience a far less certain guide to future conflict. Central to this new concept of defense management is the acceptance by decisionmakers of policy advice provided by systematic analytic studies. Such studies by engineers and physical and social scientists working as part of, or in collaboration with, the military services and the Department of Defense have thus become an essential part of the policymaking process.

In scope, these studies range from attempts to increase the efficiency of the routine peacetime housekeeping operations of the Armed Forces to advising decisionmakers on the broadest issues of national security. In its research for the United States Air Force, The RAND Corporation has played a leading role in developing an approach to the full range of these problems and in bringing the methods used to national attention. This approach, which we call "systems analysis," is the subject of this book.

## DEFINITION OF SYSTEMS ANALYSIS

What is systems analysis? Most of the defense community interprets the term narrowly, restricting it to the application of quantitative economic analysis and scientific methods to such matters as weapon design and the determination of force composition and deployment. But systems analysis is not a method or technique; nor is it a fixed set of techniques. Because systems analyses take their character largely from the problems they address, they often seem to bear little resemblance to each other. The techniques used differ from study to study, and there is but the thinnest thread of method that ties these studies together. Similarly, the problem addressed and the questions asked about the problem will induce a wide variation in the specific form of the results. It would, therefore, also be a mistake to define systems analysis in terms of the reports or briefings to which it leads, as if to say that this or that document, all starched and fresh, was "a systems analysis." This is, of course, a useful shorthand, and the authors of this book are not alone in depending on it, but it tends to blur the fact that systems analysis is actually what goes on before such documents can be prepared – and this includes all the false starts. If, then, systems analysis is not a method, a set of techniques, or a type of report, what is it?

We would suggest that, properly speaking, it is a research strategy, a perspective on the proper use of the available tools, a practical philosophy of how best to aid a decisionmaker with complex problems of choice under uncertainty. In the absence of a good brief definition, systems analysis, as the term is intended to be understood in this book, can be characterized as *a systematic approach to helping a decisionmaker choose a course of action by investigating his full problem, searching out objectives and alternatives, and comparing them in the light of their consequences, using an appropriate framework – in so far as possible analytic – to bring expert judgment and intuition to bear on the problem.*

## ORIGINS

The idea that analytic techniques might be applied to policy and strategy formulation in the military establishment was suggested by the success of operations analysis in dealing with military operations in World War II. Operations analysis became a more or less formal and distinct occupation early in that war, although much the same type of analysis was done on occasion in earlier wars[1] and even in very ancient times. The major impetus to this activity was provided by the introduction of new weapons based on, and requiring for their operation, technical know-how foreign to past military experience. These weapons and weapon systems (radar is the outstanding example) were so novel in concept and design that their exploitation could not be planned purely on the basis of traditional military experience. The questions addressed were largely tactical: how first

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[1] For instance, some of the work done by the Statistical Branch of the General Staff, U.S. War Department, during the first World War, under the direction of Colonel Leonard P. Ayres.

to use "window" or "chaff" as a radar countermeasure; how to determine more effective bombing patterns; how to determine better antisubmarine search procedures; or how to deploy destroyers to best protect a convoy. New methods of analysis had to be developed. These formed the beginnings of a body of knowledge called at that time "operations analysis" and later, in its various extensions, "operations research," "systems engineering," "management science," "cost-effectiveness analysis," and, by RAND, "systems analysis." The term "systems analysis" came into use because the first postwar efforts were concerned with the selection and evaluation of weapon systems for development. Since development requires several years, these studies no longer dealt exclusively with those operations for which the inputs were known, the objectives clear, and the uncertainties limited.

Later, around 1950, weapon system analysts (particularly at The RAND Corporation) began an attempt to include issues of national security policy and strategy in their research and to make these issues the subject of studies in themselves. The initial reaction of experienced "military analysts" in the Pentagon was cool indeed. They argued that because military policy and other large national security problems were so different from the questions of weapon systems optimization and selection that RAND and others had been reasonably successful in answering, there was little chance that the techniques and concepts of the original systems studies would carry over. Strategy and policy planning were arts, and would remain so.

Fortunately, these skeptics were only partially right. It is true that additional concepts and methodologies, significantly different from those of earlier analysis, have had to be developed. But there has been a large transfer and substantial progress. In fact, recent years have seen a dramatic increase in the extent to which analysis, in this broader sense, has influenced decisionmakers on even the most critical issues of national security.

### RELATION TO OTHER TYPES OF ANALYSIS

Systems analysis is sometimes described generally as the application of the scientific method to problems of economic choice. In no case, military or nonmilitary, is it scientific research, however. Its objective, in contrast to that of pure science, is primarily to recommend – or at least to suggest – policy, rather than merely to understand and predict. Thus, it is more nearly engineering than science. For the purposes of making a distinction here, one might say that science seeks to find things out, while engineering uses the results of science to do things well and cheaply. Yet *military* systems analysis differs from ordinary engineering in its enormous responsibility, in sometimes being forced by the nature or urgency of a problem to substitute intuition for verifiable knowledge, in the unusual difficulty of appraising – or even discovering – a value system applicable to its problems, and in the absence of ways to test its validity.

The difference between the various extensions of World War II operations analysis is largely a matter of terminology or emphasis. There are no differences in principle, and hence no clear lines of demarcation can be drawn.

The analyst who practises operations research is usually trying to use mathematics, or logical analysis, to help a client improve his efficiency in a situation in which everyone has a fairly good idea of what "more efficient" means. He rarely has to concern himself with discovering the purpose of the operation or how to tell whether it is successful or not. A major aim is to develop common structures (or "models") relevant to a wide variety of situations.

Someone has remarked that systems analysis is to operations research as strategy is to tactics. At the national policy level, this is certainly the case.

> . . . Systems Analysis . . . differs in scope from Operations Research in the conventional sense, and it is not performed exclusively or even primarily by people who might be identified as operational researchers ... It is a discipline with a logic of its own, similar in many respects to that of Operations Research, but also different in some fundamental aspects.
>
> Like operations research, this kind of analysis can and must be honest, in the sense that the quantitative factors are selected without bias, that the calculations are accurate, that alternatives are not arbitrarily suppressed, and the like. But it cannot be 'objective' in the sense of being independent of values. Value judgments are an integral part of the analysis; and it is the role of the analyst to bring to light for the policy-maker exactly how and where value judgments enter so that the latter can make his own value judgments in the light of as much relevant information as possible.
>
> Again, analysis at this level cannot prove the optimality of any national security policy. I don't doubt for a moment that, given a specified set of ships and aircraft and equipment, and a particular task such as tracking down and killing submarines in a given area, operations analysis can indicate the optimal way to go about doing it. There, only one value judgment enters in. That is, that it is desirable to kill enemy submarines. You cannot do that at the national policy level. Rather, at that level, analysis can only trace out implications of alternative policies.[2]

These more comprehensive studies also involve, at one point or another, a comparison of the possible alternative courses of action in terms of their effectiveness and costs. This comparison often requires major attention and, by a natural substitution of the part for the whole, the entire study is sometimes called a cost-effectiveness analysis. Such an analysis typically stresses the selection, from among the available alternatives, of a "least-

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[2] Alain C. Enthoven, Assistant Secretary of Defense (Systems Analysis), "Operations Research and the Design of the Defense Program," in *Proceedings of the 3rd International Conference on Operational Research*, Dunod, Paris, 1964, pp. 530, 534.

cost" scheme for carrying out some specified task. Because the analyst usually accepts as inputs someone else's statement of the objectives of the system and the possible alternatives, his results may not represent a complete systems analysis. In contrast, the systems analyst is the fellow who is likely to be forced to deal with problems in which the difficulty lies precisely in deciding what ought to be done, not simply in how to do it. He thus puts greater attention on the suitability of the task and the augmentation of alternatives. The staff study, by the way, lies in here somewhere: it may be a systems analysis, although frequently time allows little chance to make it as quantitative or complete as the ideal systems analysis would be.

This distinction between systems analysis and cost-effectiveness analysis can perhaps be clarified by a homely example.

Suppose T. C. Mits has decided to buy a washing machine for his wife. His objective is fairly clear and the alternatives are probably well-defined. If so, the situation is one for a cost-effectiveness analysis. The available machines have differences in both performance and cost. With a little care, making due allowance for uncertainty about maintenance, water, and electrical costs, he can then estimate, say, the five-year procurement and operating cost of any particular machine, and do so with a feeling that he is well inside the ball park. He will discover, of course, that finding a standard for measuring the effectiveness of the various machines is somewhat more difficult. For one thing, the problem is multidimensional – Mr. Mits must consider convenience, length of cycle, load capacity, residual water in the clothes, and so forth. But ordinarily one consideration – perhaps capacity – dominates. On this basis, he can go look at some machines, compare costs against capacity, and finally determine a best buy.

Now suppose Mr. Mits has simply decided to spend more money and thus increase his family's standard of living – a decision similar to one to strengthen the U.S. defense posture by increasing the military budget. How can he decide how to allocate the money among various possibilities? This is a situation for systems analysis, and he should probably call in his wife. Together, they first would need to investigate their goals or objectives, and then establish criteria, determine measures of effectiveness, look into the full range of alternatives – a new car, a piano, a trip to Europe. Here, because the alternatives are so dissimilar, determining what they want to do is the major problem; determining what it costs and how to attain it may become a comparatively minor one.

## THE NEED FOR ANALYSIS

The acceptance of systems analysis at the national policy level has been due in part to the success of its forerunners in World War II and the Korean

War, and to the impressive record of its extensions since that time in helping to solve complex problems in the military and in business and industry. A more important reason, however, has simply been the recognition that in the present state of the world a need exists for an analytic approach to national security problems. The radical changes in the weapons of war that began in 1945 and are still in process today strongly imply that military experience relevant to large-scale war may no longer provide adequate guidance. Nations – particularly the United States and its major potential enemies – are vulnerable in totally new ways, and military preparations can never again be put off until after hostilities have started. The capability of traditional methods of decisionmaking, based largely on policies of making incremental changes to permit the steady gaining of experience, has thus declined. Both the military professional and his civilian co-worker have been driven to the use of analytic methods to devise reasonably adequate and meaningful substitutes for experience: without calculation there is no way to discover how many missiles may be needed to destroy a target system, or how arms control may affect security.[3]

In addition, the magnitude of the defense effort is now so great that it invites critical scrutiny. As long as the total national defense requirements in peacetime were not a significant part of the national product, the country managed to survive very well with the "requirements" approach to national security planning. This approach made little use of analysis as we know it today. It proceeded in several steps. First, in the light of "national objectives" and "sound military doctrine," each service determined the kinds of military capabilities it needed. Next, by considering the technological possibilities and the operating constraints – for example, certain missions were prohibited to the Air Force – each service determined how it would like these capabilities to be obtained. The services then appraised enemy capabilities and prepared estimates of the number of items they would require. Finally, they submitted these estimates to budget authorities, who weighed them with little more than intuition as a guide and usually ended up cutting them by appeals to "national fiscal limitations." We could afford a large measure of inefficiency then. But today national security requires a more efficient utilization of resources.

To obtain it, defense decisions now depend heavily on systems analysis, applied within the context of a modern management system, known as the Planning-Programming-Budgeting System (PPBS). Program budgeting, as it is often called for short, is designed as a tool for the formulation and

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[3] This is not to say that every aspect of such problems can be analyzed, much less quantified, or that analysis is without its defects, but only that it is not sensible to formulate national defense policy without careful consideration of whatever relevant alternatives can be discovered.

continuous review of defense programs. Its distinguishing characteristics fall into three categories: (1) a budget format that indicates planned expenditures over an extended period in terms of the national security objectives these expenditures are expected to attain; (2) a management information system to keep track of expenditures and the progress of programs and to provide data for analysis; and (3) systems analyses, at all levels of activity, to search out, examine, and evaluate possible courses of action.[4] In their modern form, the ideas for the PPBS were first proposed by David Novick of RAND's Cost Analysis Department and were brought to the Defense Department in 1961 by Charles Hitch when he left RAND to become Assistant Secretary of Defense, Comptroller. In implementing this change in management practices in something less than two years, Mr. Robert McNamara, the Secretary of Defense, established himself as the foremost military administrator of our time. The implications of this system – President Johnson called it revolutionary and directed that it be implemented in all Federal departments and agencies[5] – are vast; the methods are being studied with interest throughout the world, and, at least in the United States, are now being adopted by civil administrators at all levels of government.

### TYPES OF APPLICATIONS

Analytic techniques can be applied to military problems which range from routine day-by-day operations of the services to critical onetime decisions of national security. This spectrum may be divided into the following categories:

1. Management of operations;
2. Choice of tactical alternatives;
3. Design and development of weapon systems;
4. Determination of major policy alternatives.

Roughly speaking, the order here increases with respect to the policy level involved and decreases with respect to the ability of analysis to produce firm and actionable recommendations. While the division is fairly arbitrary, and there is considerable overlapping, it will allow us to make certain broad distinctions that will help to set later discussions in place. With these qualifications in mind, let us consider Fig. 1.1, which illustrates typical problems attempted in each category.

In the first category, analysis takes its most mathematical – and, in a certain sense, its most fruitful – role. Except for the context, much of the

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[4] See David Novick (ed.), *Program Budgeting: Program Analysis and the Federal Budget*, Harvard University Press, Cambridge, 1965.

[5] "Transcript of the President's News Conference on Foreign and Domestic Matters," The New York *Times*, August 26, 1965.

based overseas without weakening our military capabilities, prestige, or alliances.

It should be emphasized that systems analysis is by no means exclusively military, but is used extensively by managers and engineers in large industrial enterprises, such as telephone companies and electric power utilities. In two respects, however, the normal business systems analysis is conceptually simpler. For one thing, in such analyses there is usually a single over-all objective – the maximization of profits – which can be measured and expressed in the same terms as the costs. For another – as we have already seen – conflict plays only a minor role.

It should also be emphasized that systems analysis has other nonmilitary applications. As the central tool of the program budgeting effort, the potential applications of systems analysis are being explored throughout the Federal government for every possible social, technological, and governmental purpose. Hailed as the most valuable by-product of the national defense and space effort, it is being touted as the vehicle to convey recent scientific and technological advances directly into the life of the ordinary citizen. Bills have been introduced in both houses of Congress "to mobilize and utilize the scientific and engineering manpower of the Nation to employ systems analysis and systems engineering to help fully employ the Nation's manpower resources to solve national problems."[8] The uses of systems analysis are also being explored on other levels of government. In California, for example, major problem areas of concern to the state have been subjected to systematic analysis by engineers of a number of aerospace firms: transportation systems (North American Aviation), criminal justice and the prevention of delinquency (Space-General), the flow of information needed for the state's operation (Lockheed), the control and management of wastes (Aerojet-General), regional land-use information systems (TRW Systems), and the state's social welfare operations (Space-General).[9]

One further point. Analyses in the later categories frequently include studies in the earlier categories as components. Often it is the completion of these component studies which absorbs most of the man-hours and makes the broader analysis possible. Nevertheless, the solution of broad military problems depends only in slight part on the narrowly technical and traditional disciplines of the natural or social sciences or engineering – and still less on the knowledge that can be found stored away in textbooks. There are no experts in this field in the sense that there are experts in navigation or in thermodynamics. Any advice that is given must come as the

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[8] H. R. 14076, 1st session, 89th Congress (1966), 213.

[9] "Aerospace 'Think Tanks' Getting Earthy Look," Los Angeles *Times*, August 14, 1966, p. I-1.

result of study applied to the particular situation, not as a deduction from some well-established theory.

A broad systems study usually makes use of an interdisciplinary team. This is not merely because a broad study is complex. Even more important is that the questions it raises will look different to an economist, a mathematician, a lawyer, a political scientist, an engineer, or a military professional – and different ways of looking at a problem are of first importance in finding a solution.

### THE ESSENCE OF SYSTEMS ANALYSIS[10]

The idea of an analysis to provide advice is not new and, in concept, what needs to be done is simple and rather obvious. One strives to look at the entire problem, as a whole, in context, and to compare alternative choices in the light of their possible outcomes. Three sorts of inquiry are required, any of which can modify the others as the work proceeds. There is a need, first of all, for a systematic investigation of the decisionmaker's objectives and of the relevant criteria for deciding among the alternatives that promise to achieve these objectives. Next, the alternatives need to be identified, examined for feasibility, and then compared in terms of their effectiveness and cost, taking time and risk into account. Finally, an attempt must be made to design better alternatives and select other goals if those previously examined are found wanting.

Even though the concept is simple in practice, the actual conditions of the analysis pose many problems, some of which we have already mentioned. At bottom, these difficulties arise because systems analysis itself and the entire process of policy planning lack an accepted theoretical foundation. Since analysts and decisionmakers alike are thus faced with serious problems of choice that yield only partially to quantitative reasoning, they are forced sooner or later to rely on the judgment, largely intuitive, of specialists with experience in the field. *The approach that makes this possible – and, hence, the very essence of systems analysis – is to construct and operate within a "model"* – an idealization of the situation appropriate to the problem. Such a model, which may range from an elaborate computer program to a war game played on a sand table, introduces a precise structure and terminology that serve primarily as an effective means of communication, enabling the participants in the study to make their judgments in a concrete context. Moreover, through feedback – the results of computation or the countermoves in the war game – the model helps the decisionmaker, the analysts, and the experts on whom they depend to arrive at a clearer understanding of the subject matter and the problem.

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[10] The notions discussed in this section and the one following are considered at length in subsequent Chapters, especially 3, 4, 7, and 10.

### THE ELEMENTS OF ANALYSIS

The central importance of the model can be seen most readily, perhaps, by looking at its relation to the other elements of analysis. There are five altogether. Each of them is present in every analysis of choice, although they may not always be explicitly identified.

1. *The objective* (*or objectives*). Systems analysis is undertaken primarily to help choose a policy or course of action. The first and one of the most important tasks of the systems analyst is to discover what objectives the decisionmaker is, or should be, trying to attain through the options open to him, and how to measure the extent to which they are, in fact, attained. This done, strategies, forces, or equipment are examined, compared, and chosen on the basis of how well and how cheaply they can accomplish these objectives.

2. *The alternatives.* The alternatives are the means by which it is hoped the objectives can be attained. They need not be obvious substitutes or perform the same specific function. Thus, to protect civilians against air attack, shelters, "shooting" defenses, counterforce attack, and retaliatory striking power are all alternatives.

3. *The costs.* The choice of a particular alternative for accomplishing the objectives implies that certain specific resources can no longer be used for other purposes. These are the costs. In analyses for a future time period, most costs can be measured in money, but their true measure is in terms of the opportunities that they preclude. Thus, if we are comparing ways to eliminate guerrillas, the injury or death of nonparticipating civilians caused by the various alternatives must be considered a cost, for such casualties may recruit more guerrillas.

4. *A model* (*or models*). A model is a representation of reality which abstracts the features of the situation relevant to the question being studied. The means of representation may vary from a set of mathematical equations or a computer program to a purely verbal description of the situation, in which judgment alone is used to assess the consequences of various choices. In systems analysis, or any analysis of choice, the role of the model (or models, for it may be inappropriate or absurd to attempt to incorporate all the aspects of a problem in a single formulation) is to estimate the consequences of the choice; that is, the costs that each alternative will incur and the extent to which each alternative will attain the objective.

5. *A criterion.* A criterion is a rule or standard for ranking the alternatives in order of desirability and indicating the most promising. It provides a means for weighing cost against performance.

The process of analysis takes place in five overlapping stages. In the first, the formulation stage, the issues are clarified, the extent of the inquiry limited, and the elements identified. In the second, the search stage, information is gathered and alternatives generated. The third stage is evaluation; the fourth, interpretation; and the fifth, verification.[11]

To start the process of evaluation or comparison (see Fig. 1.2), the various *alternatives* (which may have to be discovered or invented as part of the analysis) are examined by means of the *models*. The models tell us what consequences or outcomes can be expected to follow from each alternative; that is, what the *costs* are and the extent to which each *objective* is attained. A *criterion* can then be used to weigh the costs against performance, and thus the alternatives can be arranged in the order of preference.

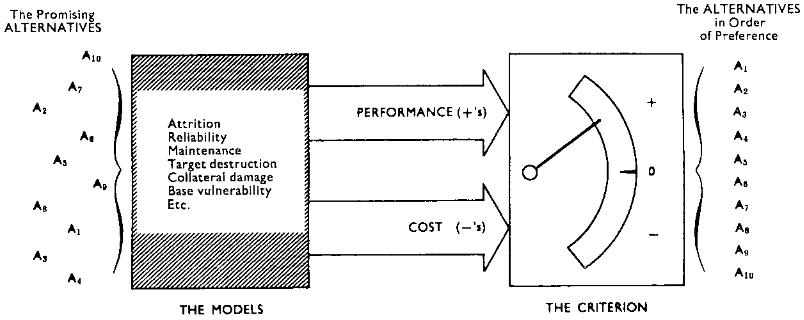

Fig. 1.2 – The structure of analysis

Unfortunately, things are seldom tidy: Too often the objectives are multiple, conflicting, and obscure; alternatives are not adequate to attain the objectives; the measures of effectiveness do not really measure the extent to which the objectives are attained; the predictions from the model are full of uncertainties; and other criteria that look almost as plausible as the one chosen may lead to a different order of preference. When this happens, we must take another approach. A single attempt or pass at a problem is seldom enough. As indicated in Fig. 1.3, the key to successful analysis is a continuous cycle of formulating the problem, selecting objectives, designing alternatives, collecting data, building models, weighing cost against performance, testing for sensitivity, questioning assumptions and data, re-examining the objectives, opening new alternatives, building better models, and so on, until satisfaction is obtained or time or money force a cutoff.

Note that there is nothing really new about these procedures. They have been followed more or less successfully since ancient times. The need for considering cost relative to performance must have occurred to the earliest planner. Systems analysis is thus not a catchword to suggest we are doing

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[11] We shall discuss these five stages in detail in Chapter 3.

something new; at most, we are doing something better – "better" in deliberately attempting to be systematic, analytic, and comprehensive, in making use of mathematical and computer techniques, and in paying careful attention to sensitivity.

## DEVELOPMENT OF SYSTEMS ANALYSIS

Although systems analysis has, in fact, contributed substantively to long-range defense planning, the contribution has not been uniform over the range of problems to which it has been applied. In the early days of systems analysis, the studies were highly preoccupied with the analytic techniques of operations research – linear programming and game theory, for example. Complicated mathematical models, featuring an astronomically large number of machine computations designed to pick out the optimum system, were popular. We soon realized, however, that real-world defense planning was too complicated for such a purely quantitative approach. Nevertheless, at the start, problems concerning strategic bombing or air defense received a good deal more attention than those, say, of limited war. This was not surprising; limited war is obviously a tri-service problem and full of factors – political, social, and economic – that cannot be easily quantified.

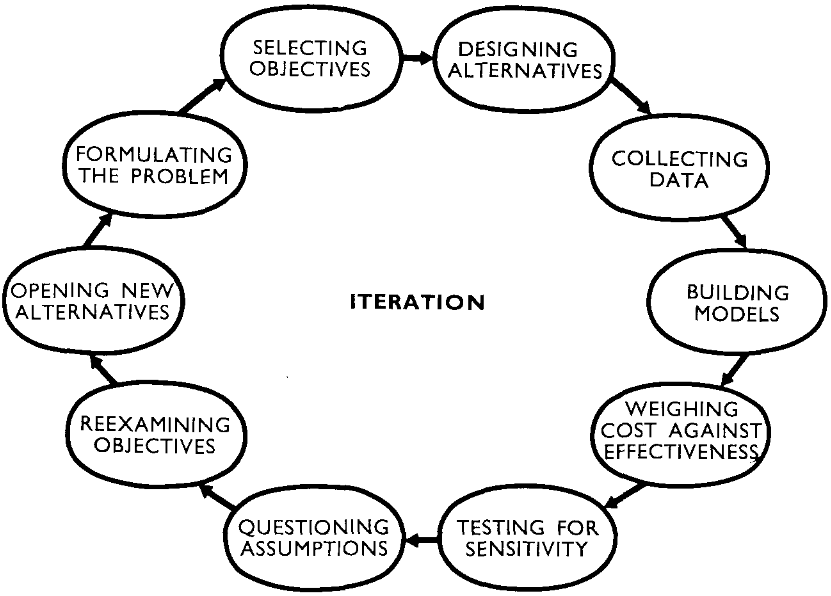

Fig. 1.3 – The key to successful analysis

When the first systems analysis was done, central war problems looked relatively free of such clutter. It was not obvious until much later that this appearance was deceiving, and that attention must be given to such aspects of strategic war as initiation, intra-war deterrence and negotiation, termination, and recovery.

Today, analyses no longer look as "analytical" as they did in the past. To an increasing extent they deal with strategy as well as with tactics – with the ability to achieve general foreign policy objectives, rather than merely with the ability of weapon systems to influence the character of a single military clash. As advisors, our objective is *insensitivity* as frequently as it is optimization: we seek to define systems that will work well under many widely divergent contingencies and even give some sort of reasonably satisfactory performance under a major misestimate of the future. Thus, RAND's first defense study focused its attention on the tactics for shooting down enemy bombers. Today, the corresponding study would look for the less obvious values of defense, relate active defense to other military missions, consider the use of warning systems for surveillance and related "nonspasm" uses, investigate the different kinds of contingencies in which defense might be useful, and so on. We now realize that the impact of subjective considerations – such as the system's flexibility, its compatibility with other systems (some yet unborn), its contributions to national prestige abroad, and its effect on domestic political constraints – can play as important a role in the choice of alternatives as any calculation of war outcomes. In addition, we realize that such intangibles as the extent to which superiority in residual forces can be effectively used to coerce the enemy to discontinue the conflict, or the perception each side has of its own or its enemy's strengths, must be taken into account. Thus, it should be no surprise that many of the component studies, and even a major part of the over-all analysis, are verbal rather than quantitative in nature.

### THE CURRENT STATUS OF SYSTEMS ANALYSIS

Where they can be obtained, quantitative estimates of costs and effectiveness are clearly helpful to any intelligent discussion of national security. In current Department of Defense practice, these quantitative estimates are now obtained as part of the programming-planning-budgeting process. The analytic part of this process is systems analysis as we have ideally defined it. But many people – some of them, perhaps, readers of this book – are vaguely uneasy about the particular way these estimates are made and their increasingly important role in military planning. This is especially so when cost-effectiveness or the use of computers is mentioned.

For example, an Air Force officer writes that computer-oriented planning techniques are dangerous; that mathematical models of future wars are inadequate for defense planning; and that scientific methods cannot handle those acts of will which determine the conduct of war.[12] A Congressman says, "We should not allow cost-effectiveness to cost us our effectiveness in national security matters."[13] A Senator remarks, "Our potential enemies may not use the same cost-effectiveness criteria and thus oppose us with the best weapons their technology can provide. This would create an intolerable peril to the national security."[14]

The cost-effectiveness aspect of these analyses is most often criticized when it deals with engineered systems like the TFX and the nuclear-powered carrier. Just over a year ago, for instance, the House Armed Services Committee spoke of the Defense Department in these words:

> . . . the almost obsessional dedication to cost-effectiveness raises the specter of a decisionmaker who . . . knows the price of everything and the value of nothing.[15]

That Oscar Wilde's famous definition of a cynic should be quoted in such a context is remarkable. Later, the chairman, Representative L. Mendel Rivers, complaining about the inadequacy of current antisubmarine warfare capability and a program to build logistics ships in a single shipyard, remarked:

> All of this is being rationalized on the basis of cost/effectiveness studies. Do you know that the M-14 rifle costs more than a bow and arrows? From a cost/effectiveness standpoint we obviously would be better off if we went back to bows and arrows. A beer bottle filled with gasoline and stuffed with a rag wick is a fairly effective weapon at close quarters, and it is cheaper to produce than a land mine or a hand grenade. From a cost/effectiveness viewpoint, we should be collecting beer bottles and old rags.[16]

Lt. General Ira C. Eaker, USAF (Ret.), in a newspaper column entitled "Most Expensive Thing a Nation Can Buy Is a Cheaper Weapon," gave his opinion:

> One of the prime obstacles to adequate defense weapons and measures in recent years has been a hurdle called cost-effectiveness. This test applied by scientists and theorists has killed off many new weapons, urgently requested by military leaders.
>
> If Hitch applies cost-effectiveness to the curriculum at California, philosophy will have to go. It does not give the financial return to graduates which they can get from medicine, engineering or law. The department of education no doubt will be eliminated also. Teaching does not pay as well as dentistry.[17]

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[12] Col. F. X. Kane, USAF, "Security Is Too Important To Be Left To Computers," *Fortune*, Vol. 69, No. 4, April 1964, pp. 146, 231+.

[13] Representative Melvin Laird of Wisconsin, quoted in *Missile/Space Daily*, April 7, 1964, p. 161.

[14] Senator John O. Pastore of Rhode Island, quoted in *U.S. News and World Report*, January 6, 1964, p. 6.

[15] House Report 1536, May 16, 1966.

[16] *Congressional Record*, October 3, 1966, pp. A-5088-5089.

[17] Los Angeles *Times*, August 22, 1965, p. G-7. Charles J. Hitch had recently resigned as an Assistant Secretary of Defense to become Vice President for financial affairs of the University of California.

One might wonder why an approach that seems so logical is so violently opposed. Cost-effectiveness analysis seeks to increase value received (effectiveness) for the resources expended (cost). It is something we always practise when buying an automobile, or planning a vacation, or building a house. Hence, as a practical matter, it is not the method that should be under attack. The deficiencies of cost-effectiveness (or systems analysis, for that matter) exist only when the work is not competently done or when the results are used without their limitations in mind. And in this connection it is worth noting that those who have used cost-effectiveness extensively have a high opinion of its value. Charles J. Hitch, for example, in speaking of the critics, remarks:

> In a way, it is quite ironic that the very people who are so insistent that they want "the best and most modern" in Defense hardware are opposed to the "best and most modern" in Defense analysis and decisionmaking techniques.[18]

We might add that those who hold that national defense decisions are being made solely by considering calculations and numbers are not only premature in their belief (to say the least), but probably have a basic misunderstanding of how such decisions must, in fact, be made. Even a nodding familiarity with the process reveals that it is today rampant with dogma, service rivalries, special interests, and horse-trading – so much so that, in the opinion of some analysts, a computerized solution that paid no attention to these human constraints might lead to something better. This book will attempt to show, however, that even in the narrowest of military contexts, considerations not subject to rigorous, quantitative, computer-based analysis are always present – and that this situation is not likely to change. At best, calculations by themselves give us, for each set of specific assumptions – about the political and economic state of the world, the actions of the enemy, the outcome of various technological investigations, and so on – a somewhat less than objective appraisal of, say, the effectiveness, for a fixed cost, of proposed forces or weapons for attaining given goals. Such appraisals are not good enough; they must be supplemented by informed and considered judgment, and there are many sets of assumptions that might be chosen. As Charles Hitch once noted, "there is nothing inherent in . . . systems analysis that calls for ignoring military judgment or for relying on computers for anything other than computation . . . ."[19]

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[18] Charles J. Hitch, "Cost/Effectiveness," address before the 13th Military Operations Research Symposium, Washington, D.C., April 29, 1964.

[19] Charles J. Hitch, "Programming's Role in Defense," address before the first International Meeting of the Western Section of the Operations Research Society of America, Honolulu, Hawaii, September 1964; quoted, in part, in *Aviation Week and Space Technology*, Vol. 81, No. 15, October 12, 1964, p. 17. Incidentally, interservice rivalries and bargaining have at least the virtue of insuring that some nonquantitative considerations are not neglected.

### OBJECTIVES OF THIS BOOK

It is not easy to tell someone how to carry out a systems analysis. We lack an adequate theory to guide us. This must be expected, for systems analysis is a fairly new discipline, and history teaches us that good theory usually comes late in the development of any field and after many false starts. Where the attention of systems analysis has turned to methods, it has focused mainly on the development of mathematical techniques for handling certain specialized problems, common in the practice of operations research – rather than on building a basic theory for the treatment of the broad questions typical in defense planning. This attention to technique *has* met with great success. Models have become easier to manipulate, even with many more variables represented, and the computational obstacles in systems analysis now cause comparatively little difficulty. The more important philosophical problems, however, such as occur in providing assurance that the model is meaningful, in devising schemes to compensate for uncertainty, or in choosing appropriate measures of effectiveness, still remain troublesome. Of the matters we could discuss in the following pages, it is these fundamental problems that most deserve a critical examination. Consequently, the many important and useful operations research techniques essential to systems analysis are treated only very cursorily. Many university and college courses, and books in profusion, handle these subjects adequately. We propose here to emphasize concepts and understanding instead – areas where the analyst as well as the user of analysis is more likely to err.

The intended reader of this book has four roles to consider with respect to analysis, for he *sponsors*, *produces*, *evaluates*, or *implements* it. The objective of this book is to provide help in each of these roles.

For the sponsor, we attempt to point out the role of analysis in the military context, what kind of analysis is appropriate to what sort of problem, and what to expect from it. At the same time, we also attempt to indicate how overspecification of the problem by the sponsor and an arbitrary determination of assumptions and methods can lead to poor results.

We also aim to help the producer of analysis. But, in viewing the producer, we are taking the approach we just mentioned, that instruction in such well-established techniques of operations research as linear programming, queuing theory, and decision theory should not be our first order of business. We feel that the real pitfalls in analyzing the broad and complex problems faced by military and government decisionmakers lie elsewhere. They concern the design and definition of the problems, the selection and understanding of rules of choice, and the interpretation of the results of analysis in the light of considerations not taken into account in the analysis. Hence, we put our emphasis on those subjects.

To assist those who must evaluate analyses, we hope to describe fully the major characteristics of good analysis and to suggest the proper questions to ask to uncover weaknesses and errors. We hope to make perfectly obvious the virtues, as well as the drastic limitations, of an analytic approach to military problems.

Finally, for those who must implement analysis, we hope to produce the kind of understanding that will provide appropriate confidence in its results.

## Chapter 2

# THE TRADE-OFF BETWEEN GROUNDPOWER AND AIR SUPPORT: AN INTRODUCTORY EXAMPLE OF SYSTEMS ANALYSIS

M. G. WEINER

*This chapter presents a highly simplified cost-effectiveness analysis of the trade-offs between groundpower and air support. Its purpose is to highlight the virtues and deficiencies of such analyses, and provide an insight into some of the principles and methods discussed in subsequent chapters.*

### INTRODUCTION

One of the most common forms of systems analysis to which the decision-maker is exposed is the "trade-off" study, part of which usually includes a cost-effectiveness analysis. A critical examination of the trade-off study should provide us, therefore, with some insight into systems analysis as a whole – how the analyst works, what he works with, what his analysis looks like, and why it looks just that way. While we could approach these questions philosophically, and talk in broad terms about the importance of assumptions, the significance of the variables or parameters chosen for a study, or how the validity of such an analysis is determined, we will instead actually go through a specific instance of a trade-off study. To keep matters within bounds, we have simplified our example considerably. Its purpose is merely to provide a vehicle for discussion, and it should not be taken too seriously. As a vehicle, it is a Model T Ford compared with some of the impressive Cadillacs that are currently in use. Nevertheless, it may get us to our destination, which is a critical appraisal of the important ingredients of trade-off studies.

First, a word or two about the differences between cost-effectiveness and trade-off analysis. A cost-effectiveness analysis is, in the simplest terms, an attempt to determine whether or not a system that might be purchased is worth the cost. To find out, it is necessary, in the first place, to formulate some notion of "worth," some "measure of effectiveness."[1] How well does the system do the job it is designed to do? Does its effectiveness warrant the cost? In many cases, these turn out to be difficult questions to answer in the military field. Take, for example, a tactical weapon system like a

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[1] A problem discussed at length by L. D. Attaway in Chapter 4.

fighter-bomber. An analyst can indeed determine *some* aspects of its effectiveness – such as the number of weapons it can deliver, its delivery accuracy, its survivability – even though he often finds that the task of expressing them quantitatively is a complex one. But his problem of measuring effectiveness becomes still more difficult when he has to add to his account of the fighter-bomber a description of characteristics like its deterrent value or political demonstration value. Moreover, the analyst must formulate estimates of costs, and here he runs into the same difficulties. He can, of course, make some fairly accurate estimates of dollar costs, but what about some of the other costs, like the political or psychological?[2] As those who have some familiarity with cost-effectiveness studies know well enough, it is easier to say that these costs should be analyzed than it is to analyze them.

If a cost-effectiveness study is a way of determining whether or not a system is worth its cost, a trade-off study is a way of determining whether or not one system is better than another. Here the difficulties are much the same as they are in cost-effectiveness analyses.

We are all familiar with cost-effectiveness and trade-off studies in our everyday life. Put in overly simple terms, any time we compare several TV sets, listing the good and bad points about each (including the cost), and then decide which one we would like "on balance," we do a cost-effectiveness analysis. And every time we compare a TV set with the new dishwasher our wife wants, we do a trade-off analysis – again going through the pros and cons and costs of each, but with somewhat greater difficulty because dishwashers and TV sets are not easily compared, and other aspects of our relations with our wife may play an important role in the final decision.

The trade-off study which we will present is a good example of the problem of trying to compare quite different things. It is a study of the trade-off between airpower and groundpower.

Now what does this mean? What exactly are we going to trade off? Can the trade-off between airpower and groundpower be reasonably expressed as a trade-off between divisions of ground forces and wings of airpower? Should it be considered for the entire spectrum of limited war, including nuclear operations? Is it dominated by one potential conflict area, such as the Far East or Europe? To what extent, if any, should some of the non-quantifiable military and non-military factors – such as the value of these forces in showing the flag – be included in the analysis? Can pure trade-offs of air and ground forces be considered, or only different "mixes" of

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[2] The nature of resource analysis and cost-sensitivity analysis is explored in Chapters 7–9. That of the more or less nonquantitative costs is considered throughout this book, especially in Chapters 3, 16, 17, 18, and 20.

the two? These and other questions must be answered, however tentatively, before analysis of force trade-offs can begin.

By the time the analyst has thought about these complex possibilities for a while he is ready to ask for reassignment. However, if this fails, he pushes on. He tries to narrow the problem down a bit. And, as every analyst knows, the minute he tries this, he provides critics with ammunition. "What about all those things which you haven't included?" they ask with a disarming smile, while the blood – usually the analyst's – drips.

But narrow down he must. So, for our purpose, we will say that the analysis will consider only the military trade-off of various mixes of divisions and wings in a non-nuclear war.

Unfortunately, this simplification has not made the task much less complicated. True, we can now state the problem more specifically, but, as analysts, we still have other major questions to face. Among the most significant is that of discovering a way of comparing the effectiveness of ground divisions and air wings.

Several bases for comparison suggest themselves: tonnage delivered, rapidity of response, ground-holding capability, casualties inflicted, casualties taken, and some others, singly or in combination. It might be objected, of course, that several of these measures are related: the tonnage delivered affects the casualties that are inflicted; the ability to hold ground is related to the ratio of casualties inflicted to casualties taken; and so on. With this variety of interrelations, we would probably want to try several different measures. But for this illustrative example, let us use "casualties inflicted" as a measure since it appears to be part of most of the others. We will therefore begin our trade-off study at that point, by comparing the casualty-producing capability of an air wing and a ground division.

### CASUALTY PRODUCTION BY AIRPOWER

What is the casualty-producing capability of airpower? It depends on many things: the situation, the type of aircraft, the number of aircraft, the types of weapons and their effectiveness, and so on. For our purposes, let us start with an assumption about the casualty-producing capability of one jet aircraft equipped with non-nuclear weapons.

Although various estimates of this capability can be obtained from historical data and analyses, they will depend on the particular conditions appropriate to each source of data. In a fuller analysis than the one attempted here, we would, of course, want to use several different values and see how each one influences the outcome of the study. We would also want to make some side investigations to obtain as valid a set of values as possible.[3]

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[3] Sensitivity analysis and the treatment of uncertainty are discussed throughout this volume. In particular, note Chapters 5, 8, 10, and 17.

But in the present example, where our aim is simply a broad sketch of trade-off analysis, we will *arbitrarily* select a number from the range of available values and say that one aircraft will produce 25 enemy casualties in each attack or sortie against organized ground units. For this illustration, we will consider these units to be enemy divisions of approximately 13,000 troops.[4]

Now, since each wing contains 75 aircraft,[5] and we can reasonably assume that each aircraft will fly one sortie a day,[6] we can calculate that one wing will produce 1875 casualties daily (75 acft × 1 sortie × 25 casualties per sortie).

### CASUALTY PRODUCTION BY GROUNDPOWER

The casualty production of groundpower must be estimated in a somewhat different manner. Using historical data, we find that the attrition of a main enemy force on the offensive (assuming an enemy superiority between 2:1 and 4:1) is 11.2 per cent casualties a month.[7] Since we are using an enemy division size of 13,000 troops in our estimates, this amounts to approximately 1500 casualties in 30 days (0.112 × 13,000), or 50 casualties a day.

### SOME ADDITIONAL ASSUMPTIONS

Having made two sets of calculations of the casualty-producing effectiveness of airpower and groundpower, we now wish to relate these to some type of conflict situation. One method of doing this is to hypothesize a conflict environment, including the forces and objectives of the antagonists in the conflict. This activity, sometimes called "scenario" construction, can be done in various degrees of detail.[8] For our purposes, we will construct a hypothetical and highly simplified non-nuclear conflict situation in which Red commits 60 divisions and Blue has 30 divisions initially available to meet the assault.[9] In addition, we will assume that Blue has 15 divisions in reserve which he can commit to combat throughout the first 30 days of combat.

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[4] Our choice of this figure of 13,000 troops as the size of an enemy division is arbitrary. The Army's *Handbook on Aggressor Military Forces*, FM 30–102 (Headquarters, Department of the Army, January 1963), cites a strength of 13,900 for a fictitious aggressor motorized rifle division.

[5] *Questions and Answers About the United States Air Force*, U.S. Government Printing Office Document 1965–0–764–115, Washington, D.C., April 1965.

[6] The sortie rate of aircraft depends on many factors. We use a rate of one sortie per aircraft per day because it approximates some actual combat experience, as indicated in *Air Force and Space Digest*, Vol. 49, No. 4 (April 1966), p. 46.

[7] Adapted from the *Staff Officers' Field Manual: Organization, Technical, and Logistical Data*, FM 101–10, Part I, Headquarters, Department of the Army, October 1961.

[8] A point that Seyom Brown will discuss more fully in Chapter 16.

[9] For convenience in what follows, we will use the nomenclature of war gaming to refer to the antagonists. Thus, "Red" denotes the aggressor's forces; "Blue" denotes the defender's forces.

For our hypothetical scenario, we further assume that both sides have considerable airpower. Blue uses the bulk of his airpower to oppose Red's air strength. He attacks Red's airfields and supply lines, and commits some aircraft to air defense. But he also commits two wings (150 aircraft) to attacking ground troops. That is, Blue flies 150 sorties per day for 30 days against enemy ground forces.

Finally, we will posit two rules. The first is that when a ground division has suffered 30 per cent casualties, it is ineffective for combat.[10] For Red, this means that about 3900 casualties (0.30×13,000 troops) will force the withdrawal of a division from combat. The second rule is that once a division has been withdrawn from combat, it cannot be replaced. In our example, this rule implies that Red cannot add new divisions to the original 60 he commits to the conflict, and this, in turn, assumes that Blue's air operations will be successful in preventing Red from bringing in reserves.

### EFFECT OF BLUE GROUNDPOWER

Let us now determine the effectiveness of Blue's groundpower in our example. Red commits 60 divisions. The attrition to each division, as calculated above, is 50 casualties a day from Blue's ground forces. This amounts to 3000 casualties for the 60 divisions each day, or 90,000 casualties in 30 days (60 divisions × 50 casualties per day per division × 30 days). Since, by our defeat criterion, each division that suffers 3900 casualties is withdrawn from combat,[11] the 90,000 casualties amount to defeating 22.5 Red divisions in 30 days. This result is portrayed graphically in Fig.

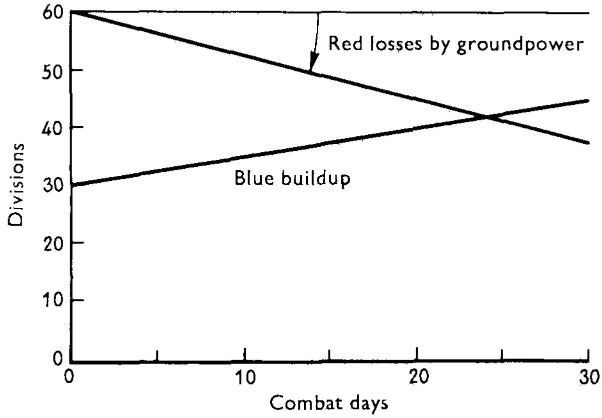

Fig. 2.1 – Effect of Blue's groundpower

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[10] While various numbers might be used as "defeat criteria" we have chosen 30 per cent of the force since it represents the approximate magnitude of casualties suffered by the Germans in the Ardennes operation of 1944–1945.

[11] For convenience, we will use the figure of 4000 casualties in the following calculations.

2.1, which shows both Blue's buildup and the reduction in Red's ground force strength for the 30-day period.

### EFFECT OF BLUE AIRPOWER

The effectiveness of Blue's airpower is calculated in the same manner. Against a Red force of 60 divisions, the two wings of Blue aircraft in ground support will produce 3750 casualties per day (two wings × 1875 casualties per day, the casualty rate calculated earlier). For the 30-day period, this amounts to 112,500 Red casualties, or the defeat of approximately 28 divisions (112,500/4000). This result is shown graphically in Fig. 2.2.

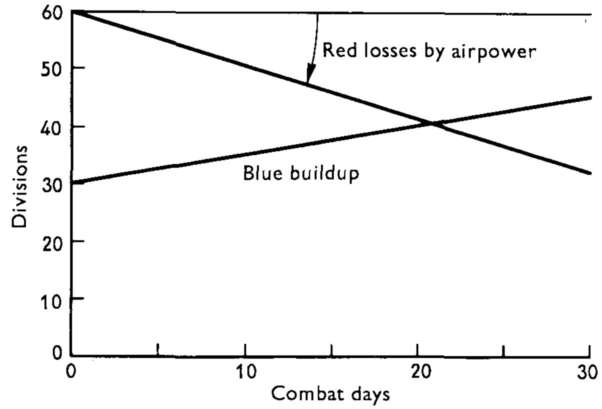

Fig. 2.2 – Effect of Blue's airpower

### COMBINED EFFECTS OF AIRPOWER AND GROUNDPOWER

If, as is done in Fig. 2.3, we combine the effects of airpower and groundpower, we see that the total reduction in Red strength over the 30-day period will be 50.5 divisions: 22.5 divisions from groundpower, 28 divisions from airpower. Further, we find that the ground situation is stabilized on approximately the 14th day of combat; that is, on that day, both Red and Blue have the same number of ground divisions in combat.

### EFFECT OF BLUE FORCE ATTRITION

Thus far, we have not estimated the attrition of Blue's ground forces. Because we have assumed that Blue's air operations are successful in preventing Red's aircraft from making any substantial contribution to the ground campaign, we need account only for the attrition produced by Red's ground forces. This can be calculated as it was for Red's ground forces, although corrections must be made to reflect the fact that Blue's ground forces are on the defensive and numerically smaller. In these terms, Blue's total attrition in the ground campaign amounts to the defeat of approximately 14 divisions in 30 days.

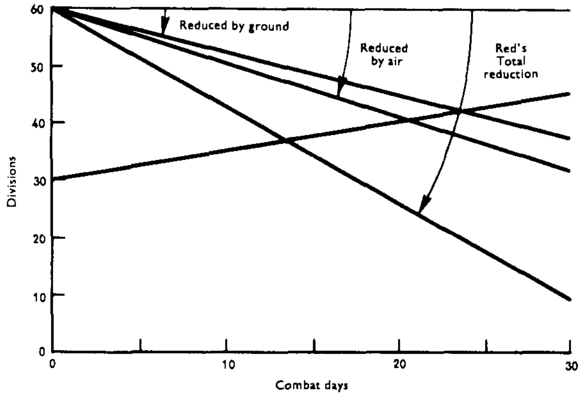

Fig. 2.3 – Combined effects of airpower and groundpower

If we compare our calculations of Red and Blue attrition, we find (Fig. 2.4) that the situation becomes stabilized in approximately 18 days; that is, the ground forces on each side are then of equal strength.

### OTHER AIR-GROUND FORCE MIXES

Our calculations so far have assumed 60 Red divisions, 30 Blue divisions initially (plus 15 more from mobilization), and two wings of Blue aircraft in ground support. We can, of course, look at other combinations, among them these four:

1. Twenty-five Blue divisions plus 15 from mobilization.
2. Thirty-five Blue divisions plus 15 from mobilization.
3. Each of the above ground strengths with only one wing of Blue aircraft in ground support.
4. Each of the above ground strengths with three wings of Blue aircraft in ground support.

In considering each of these possibilities, we will leave unchanged our assumptions regarding Red's initial ground strength (60 divisions), the defeat criterion for a division (30 per cent casualties), and Red's inability to bring additional reserves into the ground campaign.

Calculating as before for each of these mixes, we can derive the results shown in Fig. 2.5. Of the various stabilization points that can be identified, we have indicated two on the Figure (the black dots). These points show the alternative mixes of airpower and groundpower that produce stabilization on the 16th day, and it is these two equal-effectiveness mixes we shall want to trade off.

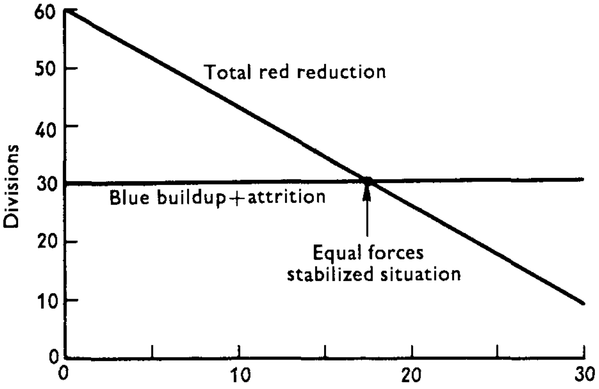

Fig. 2.4 – Effect of Blue's force attrition

## COSTS

At this point, we can introduce cost considerations. Expressing them as simply as possible, we can assume that one wing of the aircraft we are concerned with here will cost $400 million,[12] and one Blue division will cost just twice as much.[13] These figures are taken to include initial investment plus 5-year operating costs.

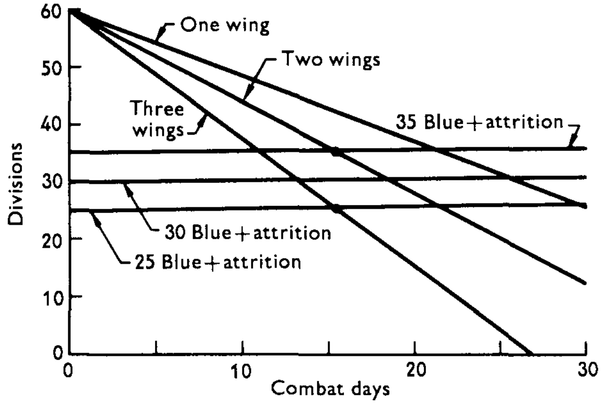

Fig. 2.5 – Effect of various air-ground mixes

## TRADE-OFF CONCLUSIONS

Using these cost data and the earlier measures of effectiveness, we can

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[12] This value is based on an arbitrary assumption of an initial investment cost of $2.0 million each for 75 aircraft plus $50 million a year for operating costs.

[13] This value is taken as the average of the costs of all types of U.S. divisions, as given in *Aviation Week & Space Technology*, Vol. 80, No. 8 (February 24, 1964), p. 65.

now calculate the trade-off between our two mixes. For the first mix, the total cost is $28.8 billion:

2 wings at $400 million = $0.8 billion
35 divisions at $800 million = $28.0 billion
Total = $28.8 billion

For the second mix, the total cost is $21.2 billion:

3 wings at $400 million = $1.2 billion
25 divisions at $800 million = $20.0 billion
Total = $21.2 billion

The difference in cost between the two is $7.6 billion. Thus, since both mixes lead to a stabilized conflict situation on the same day of combat, we can conclude that the second mix will produce *a saving of* $7.6 *billion over the first mix, without any loss of effectiveness.*

### SOME LARGER CONSIDERATIONS

As far as systems analysis is concerned, it is appropriate to conclude this illustration by asking two major questions: First, "Is this study adequate?" Second, "If not, why not?"

Is there an aspect of this analysis that seems suspicious? If so, what is it? Is it the statement of the problem as a trade-off and cost-effectiveness analysis? Is it that the problem was narrowed down to a mix of wings and divisions? Is it the assumptions made in the scenario about the Red or Blue air or ground forces? Is it the criterion that we specified (the casualty-producing capability of our airpower and groundpower) or the way we calculated it? Is it the "pay-off" measure (length of the conflict) that we used? Is it the data we used on the effectiveness of airpower and groundpower? Is it our selection of alternative mixes of divisions and wings? Is it the cost estimates? Is it the conclusions we drew about trade-off savings and equal effectiveness? Or is it something else?

If the analysis is not credible, is it possible to pinpoint the reason why, or the remedies that might be taken?

The answer should be "yes." Despite the volumes of calculations, the detailed scenarios, the pages of analytic data, the computer programs and outputs, the war games, or the mathematical formulae that are part of many systems analyses, the basic structure of an analysis is usually simple. If the user or doer of an analysis cannot identify this structure and examine it critically, he may not understand what the analysis is all about, or whether or not it is valid. In short, it is the structure, rather than all the supporting data, calculations, games, computer programs, and so on, on which the analysis must stand or fall.

The remainder of this book, in various ways and from various points of view, elaborates on this theme and some others implied in our example. In Chapter 21, we will return specifically to the example and attempt to see, in the light of what the authors in between have had to say, how the analysis might have been designed and conducted differently.

## Chapter 3

# PRINCIPLES AND PROCEDURES OF SYSTEMS ANALYSIS

## E. S. QUADE

*This chapter surveys the "hows" of systems analysis and the "whys" behind them. Its basic purpose is to provide an overview of, and a context for, the individual questions of theory and technique discussed in detail by the following authors. Accordingly, the chapter limits itself to a general description of the steps common to all analysis; the principles governing each; their interaction; the character of the results they permit; the utility of these results for the decisionmaker; and, in the broadest terms, the nature of "successful" or "good" analysis.*

### INTRODUCTION

The RAND Corporation has produced analyses of national security problems for quite a number of years – in fact, since World War II. Although collectively we have learned a great deal that should be useful to anyone attempting to analyze such problems, we have not yet learned enough to supply a sequence of steps or rules that, if followed mechanically – by the numbers, so to speak – would automatically guarantee solutions that will stand the tests of time. In the main, this is so because military systems analysis is to some extent still an art – or at least a craft – rather than a form of engineering or an exact science. It is not, like statistics or physical chemistry, say, a body of knowledge and skills that can be acquired largely without becoming involved in particular applications.

Now, of course, some techniques of an art – even some of the most important ones – can be taught, but not by means of fixed rules which need only be followed exactly. Thus, in our analyses, we must sometimes do things that we think are right but cannot really justify or even check in the output of the work. We must accept many subjective judgments as inputs, and we must present answers based partly on judgment to be used as a basis for other judgments. Hence, a discussion of "how systems analysis is done" must content itself with indicating some guidelines, some principles, and some illustrative examples.

### THE ESSENCE OF SYSTEMS ANALYSIS

If systems analysis is largely "art" and "judgment," what does the "analysis" contribute? Our answer to this question was expressed in the introductory chapter. There we stated our view that to a large extent systems analysis is successful in areas where there is no accepted theoretical foundation (defense planning is an example), precisely because it is able to make a more systematic and efficient use of expert judgment than can its alternatives. The essence of the method is to construct and operate within a model – an idealization of the situation appropriate to the problem. Such a model – in the example given by M. G. Weiner in Chapter 2, it is a series of rules or planning factors taken from official records – introduces a precise structure and terminology that serve primarily as a means of communication. As such, it enables the participants to make their judgments concretely, and, through feedback – which, in the previous example, would be the outcomes predicted by the planning factors – it helps the analysts, the experts, and the decisionmakers to arrive at a clearer understanding of both the problem and its context.

To keep the discussion from becoming too abstract, we will attempt to illustrate the points we intend to make by reference to the following hypothetical example:

Suppose a new, lighter-payload missile system is being advocated to replace or supplement the Minuteman. It would make use of the Minuteman silos and other ground facilities. Supporters claim that it will be more reliable and much more accurate and that these advantages far outweigh its somewhat higher cost and lower payload. Assume also that although development is advanced, several variants are possible, and that a decision should be made soon whether or not to freeze the design and plan procurement.

How can we proceed with an analysis to provide advice on this decision?

### THE ALTERNATIVES

Before we answer this question, we might examine briefly the alternative sources of such advice. One of the most common, unfortunately, is pure intuition. It is in no sense analytic, since no effort is made to structure the problem or to establish cause and effect relationships and operate on them to arrive at a solution. The intuitive process is to learn everything possible about the problem, to "live with it," and to let the subconscious provide the solution. Someone using this method does not feel any obligation to show how he arrived at the solution.

Between pure intuition, on the one hand, and systems analysis, on the other, there are other sources of advice that can, in a sense, be considered analytic, although the analysis is ordinarily less systematic, explicit, and quantitative. One alternative is simply to ask an expert for his opinion.

What he says can, in fact, be very helpful, if it results from a reasonable and impartial examination of the facts, with due allowance for uncertainty, and if his assumptions and chain of logic are made *explicit*, so that others can use his information to form their own considered opinion. But an expert, particularly an unbiased expert, may be hard to find. National security problems – even those like our example, which is one of the simpler types – are complex and what should be done depends on many widely different disciplines. An expert's knowledge and opinions are likely to be more valuable if they can be formulated in direct association with other experts. This suggests systems analysis, for, as remarked above, that approach, with its models and feedback, is essentially a device for providing a framework for the systematic and efficient employment of the knowledge, judgment, and intuition of the available experts.

Another way of handling a problem is to turn it over to a committee. Now, although there is no reason why a committee cannot engage in systematic analysis, this is not likely to happen. Committees are much less likely than experts to make their reasoning explicit, since their findings are usually obtained by bargaining – by the effort to reach a consensus or an acceptable compromise. How this effort can affect originality, precision, and efficiency hardly need be mentioned. This is not to say that a look by a "blue ribbon" committee into our missile problem might not be useful, but its greatest utility is likely to be in the critique of work done by others.

Answers obtained from experts working individually or as a committee depend largely on subjective judgment. *So do the answers obtained from systems analysis.* As one writer has put it:

> Subjectivity is inherent because of the essential content of political values in public policy questions. Public policy by definition pertains to human conduct – the behavior and relations among men in political society. Because of its human impact public policy – and strategy in particular – cannot be free of questions of political value and hence cannot be decided except through the exercise of human judgment. The ingredient of human judgment – be it only the simplest kind of intuition – is therefore an essential part of any study of policy, no matter how analytical. Judgment can be aided and augmented by the techniques of scientific analysis, but it can never be supplanted.[1]

But the analytic approach, in contrast to its alternatives, provides its answers by processes that are accessible to critical examination and can be retraced by others, who can modify them more or less readily on the basis of their own judgments as errors appear or as new information becomes available.

However, no matter whether the advice is supplied by an expert, a committee, or a formal study group, an *analysis* of a problem of choice involves

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[1] Col. Wesley W. Posvar, "The Realm of Obscurity," in *American Defense Policy*, prepared by Associates in Political Science, United States Air Force Academy, The Johns Hopkins Press, Baltimore, Md., 1965, p. 224.

the same five elements and basic structure we considered in Chapter 1:[2] the objectives; the alternatives for attaining them; the costs, or what we must give up; the models, which allow us to see the costs of the alternatives and the extent to which they attain the objectives; and finally, the criteria, which tell us what alternatives to choose.

We now turn to the process by which these elements are identified and the analysis carried out.

### THE PROCESS OF ANALYSIS

The process of systems analysis represents a conscious attempt to extend the approach and methods – and, ideally, the standards – of the "hard" sciences into areas where controlled experimentation is seldom possible. Unfortunately, some people have exaggerated the significance or success of this attempt, and we find them saying such things as that systems analysis and operations research are really nothing more than the "scientific method" extended to problems outside the realm of pure science. Leaving aside the question whether there is anything that might be called *the* scientific method, what such statements must mean, in part, is that the analysis advances (by iteration or successive approximation) through something like the following stages:

| | |
|---|---|
| FORMULATION<br>(The Conceptual Phase) | Clarifying the objectives, defining the issues of concern, limiting the problem. |
| SEARCH<br>(The Research Phase) | Looking for data and relationships, as well as alternative programs of action that have some chance of solving the problem. |
| EVALUATION<br>(The Analytic Phase) | Building various models, using them to predict the consequences that are likely to follow from each choice of alternatives, and then comparing the alternatives in terms of these consequences. |
| INTERPRETATION<br>(The Judgmental Phase) | Using the predictions obtained from the models and whatever other information or insight is relevant to compare the alternatives further, derive conclusions about them, and indicate a course of action. |
| VERIFICATION<br>(The Scientific Phase) | Testing the conclusions by experiment. |

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[2] See pp. 16–18 and Fig. 1.2.

All analyses involve these five activities to some extent, but often the fourth is done largely by the policy-maker and the last must be done indirectly, if at all. There is a class of problems – our missile comparison is an example – in which verification may be possible in principle, but the costs of an actual test would certainly be too high. Thus, if we want to estimate what damage our missiles might do to the Soviet Union, the best we can do is use simulation to devise a vicarious experiment.

The process of analysis may be represented as in Fig. 3.1. Here the activities appear neatly separated. This is seldom the case, however, for to one degree or another they all occur simultaneously. In our missile comparison, for example, the prescription for carrying out the work might run as follows:

1. Define and limit the problem. Are we helping to make a force posture decision or is the decision really only one of whether or not to continue a promising development?
2. Classify the objectives or goals that one hopes to attain with the system being considered. Are we striving for deterrence to prevent a nuclear attack on the United States or are we striving for an even more comprehensive deterrent?
3. Forecast the political and military environment in which the systems are to operate. Do we need to consider scenarios in which the war starts as a result of the degeneration of a crisis situation, or deliberate escalation, or, as is often done, solely an attack "from out of the blue"?
4. Determine ways to measure the degree of attainment of the goals or objectives. This requires us to identify the mission to be assigned the missiles.
5. List and define the alternative systems that offer some reasonable hope of accomplishing the objectives, and select appropriate criteria for choosing among these systems.
6. Choose the approach. Shall we compare the systems for a fixed budget or shall we first fix the mission requirement? Do we start with a computer model or a manual war game?
7. Formulate a scheme for working out the dollar costs that takes account of changes in operating philosophy and development time. Explore the nonmonetary costs. Are there significant resource restraints or are there undesirable side effects that interfere with programs?
8. Examine the risks and timing in the development. Are we seeking to advance the state-of-the-art or merely to improve current capabilities?
9. Compare the systems. Do the important differences stem from unresolvable uncertainties about the future state of the world, or are they matters of engineering?
10. Perform sensitivity analyses by varying key parameters across a

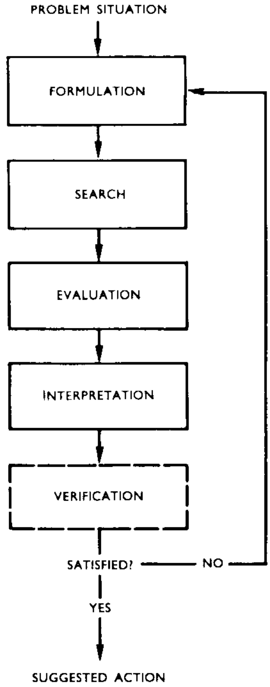

Fig. 3.1 – Activities in analysis

range of values, to see that major uncertainties are thoroughly explored.

11. Consider the factors that we have so far not taken into account, and test them against various assumptions where we think we have some knowledge of what the outcome should be.

12. Decide what we can really recommend on the basis of the analyses.

13. Document our work. This should include the rationale and assumptions, more than a mere summary.

Some of these steps are clearly part of problem formulation, others belong in the domain of the comparison, and still others might be classified as part of the interpretation stage. The search stage, as is typically the case, permeates the whole process and is especially difficult to isolate as a separate activity. If, however, we stand back from the clutter of the real world, there are several points we can usefully make about the process of analysis as it appears in each of the activities named in Fig. 3.1. Let us take them in turn, beginning with "Formulation."

### *Formulation*

Formulation implies an attempt to isolate the questions or issues involved, to fix the context within which these issues are to be resolved, to clarify the objectives, to discover the variables that are operative, and to state relationships among them. These relationships may be extremely hypothetical if empirical knowledge is in short supply, but they will help make the logical structure of the analysis clear. In a sense, formulation is the most important stage, for the effort spent restating the problem in different ways or redefining it clarifies whether or not it is spurious or trivial and points the way to its solution.

The process of formulation is highly subjective. We must, for example, consider what evidence will be meaningful and significant to the decision-maker we are trying to help. Thus, in our missile comparison, will it be sufficient to compare the new missile with the Minuteman alone, or must other missiles or even manned bombers be considered? Will it be adequate to make the comparisons in a U.S. second strike situation? Greater reliability and accuracy may show to more advantage in wars initiating in other ways. Are we helping to make a force posture decision or should we really only be trying to demonstrate that we have a promising development that should be continued for its growth potential alone?

The tendency all too frequently is to accept the client's original statement of what is wanted, and then to set about building a model and gathering information, scarcely giving a thought to whether the problem is the right problem or how the answer will contribute to the decisions which it is meant to assist. In fact, because the concern is with the future, the major job may be to decide what the policy-maker should want to do. Since systems studies have resulted in rather important changes, not only in how the policy-maker carries out his activity, but in the objectives themselves, it would be self-defeating to accept without inquiry the customer's or sponsor's view of what the problem is.

But how is the analyst to know that his formulation of the problem is superior? *His only possible advantage lies in analysis.* That is, the process of problem formulation itself has to be the subject of analysis. What this means is that, using the few facts and relationships that are known at this early stage and assuming others, the analyst must simply make an attempt to solve the problem. It is this attempt that will give him a basis for better formulation. He always has some idea as to the possible solutions of the problem; otherwise, he probably should not be working on it, for his analysis might prove to be too formal and abstract.

Let us consider a classic example. For fiscal year 1952, Congress authorized approximately $3.5 billion for air base construction, about half to be spent overseas. RAND was asked to suggest ways to acquire, construct, and maintain air bases in foreign countries at minimum cost. The analyst who reluctantly took on this problem regarded it at first as essentially one of logistics. He spent a long time – several months, in fact–

thinking about it before he organized a study team. Although he had little of the information needed to make recommendations, he was able to see the problem in relation to the Air Force as a whole. He came to the conclusion that the real problem was *not* one of the logistics of foreign air bases, but the much broader one of *where and how to base the nation's strategic air forces and how to operate them in conjunction with the base system chosen.* He argued that base choice would critically affect the composition, destructive power, and cost of the entire strategic force and thus that it was not wise to rest a decision about base structure and location merely on economy in base cost alone. His views prevailed and he led the broader study, the results of which contributed to an Air Force decision to base SAC bombers in the continental United States and use overseas installations only for refueling and restaging.[3] An Air Force committee later estimated that the study recommendations saved over $1 billion in construction costs alone. In addition, it sparked a tremendous improvement in strategic capability, particularly with regard to survival, and stimulated a good deal of additional research on related questions.

In analysis, the problem never remains static. Interplay between a growing understanding of what it involves now and might involve in the future forces a constant redefinition. Thus, the study just mentioned, originally conceived as an exercise to reduce costs, became in the end a study of U.S. strategic deterrent policy. Its recommendations led to a major reduction in SAC vulnerability; that costs were also reduced was secondary.

Primarily as the result of discussion and intuition, the original effort to state a problem should suggest one or more possible solutions or hypotheses. As the study progresses, these original ideas are enriched and elaborated upon – or discarded – and new ideas are found. The process of analysis is an *iterative* one. Each hypothesis serves as a guide to later work – it tells us what we are looking for while we are looking. As a result, the final statement of the conclusions and recommendations usually rests on a knowledge of facts about the problem which the analyst did not have at the start. In the early stages it is not a mistake to hold an idea as to the solution; the error is to refuse to abandon such an idea in the face of mounting evidence.

It is important to recognize that anything going on in one part of an activity, organization, or weapon system is likely to affect what goes on in every other part. The natural inclination in problem-solving is to select a

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[3] For the full report, see A. J. Wohlstetter, F. S. Hoffman, R. J. Lutz, and H. S. Rowen, *Selection and Use of Strategic Air Bases*, The RAND Corporation, R-266, April 1954. A nontechnical account of this study appears as Chapter VI in Bruce L. R. Smith's *The RAND Corporation: Case Study of a Nonprofit Advisory Corporation*, Harvard University Press, Cambridge, Mass., 1966.

part of the problem and analyze it separately, or to reduce the problem to one that looks manageable. "Many scientists owe their greatness not to their skill in solving problems but to their wisdom in choosing them."[4] Systems analysis, however, does not offer us this freedom, at least not at the outset. We have to solve the problem that exists. It calls for us to extend the boundaries of the problem as far as required, determine which interdependencies are significant, and then evaluate their combined impact.

But even for small-scale problems, the number of factors under consideration at any one time must be reduced until what is left is manageable. In systems analysis, the complexity of the full problem frequently far outruns analytic competence. To consider in detail anything like the complete range of possible alternative ways to deliver weapons on strategic targets may be impossible. The use of suitcases or automobiles as delivery systems does not belong in our missile comparison. Fortunately, the vast majority of alternatives will be obviously inferior, and can be left out without harm. The danger is that some alternative better than the one ultimately uncovered by the analysis might also be left out. Thus, although constraints must usually be imposed to reduce the number of alternatives to be examined, this should be done by preliminary analysis, not by arbitrary decree. Moreover, such constraints should be flexible, so that they may be weakened or removed if it appears in later cycles that their presence is a controlling factor. In analyzing our missile system, for example, we do not simultaneously seek to determine the ideal ground support weapon for the Tactical Air Command or the ratio of medical corpsmen to cooks in the base support battalion. We call such a restriction of the problem a "suboptimization."

The necessity for suboptimization compounds the difficulties in the selection of criteria and objectives. It is inevitable that not all decisions can be made at the highest level or by one individual or group; some must be delegated to others. Analysts and decisionmakers must thus always consider actions that pertain to only a part of the military problem. Other choices are set aside temporarily, possible decisions about some things being neglected and specific decisions about others being taken for granted. What is crucial is that the criteria and objectives for the suboptimization be consistent with those that would apply to the full problem.

The most troublesome problems in analysis – those of selecting criteria, objectives, and ways to measure effectiveness – are discussed in detail in the next chapter. We might note several general points beforehand, however.

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[4] E. Bright Wilson, Jr., *An Introduction to Scientific Research*, McGraw-Hill Book Company, Inc., New York, 1952, p. 1.

It is commonly supposed that goals should, and can, be set independently of the plans to attain them. Yet there is considerable evidence that operationally significant objectives are, more often than not, the result of opportunities that possible alternatives offer rather than a source of such alternatives. For one thing, it is impossible to select satisfactory objectives without some idea of the cost and difficulty of attaining them. Such information can only come as part of the analysis itself. For another, only some of the possible consequences of different alternatives can be anticipated before the analysis. The newly discovered consequences may then become goals. Thus, for example, the invention of a near-perfect system for continuous peacetime strategic reconnaissance might, in some circumstances, make a first strike to disarm the enemy an objective worth considering.

In fact, a characteristic of systems analysis is that solutions are often found in a set of compromises which seek to balance and, where possible, to reconcile conflicting objectives and questions of value. It is more important to choose the "right" objective than it is to make the "right" choice between alternatives. The choice of the wrong alternative may merely mean that something less than the "best" system is being chosen. Since we must frequently be satisfied with at most a demonstration that a suggested action is "in the right direction," this may not be tragic. For, as we shall see, such a demonstration may be the best that can be done anyway. But the wrong objective means that the wrong problem is being solved.

The choice of the objective must be consistent with higher, or national, objectives. Since these are seldom operationally defined, however, the analyst has a great responsibility to exercise care and good judgment. In our missile comparison, for instance, if we choose as an objective one that puts a great premium on keeping collateral damage and civilian casualties low, we bias the analysis toward the more accurate missile. Since in the example we are attempting to determine whether or not to replace a current capability with a more accurate one, we should select deterrence as our objective, measuring it proximately by the total mortalities inflicted, for accuracy is not so significant here. We then can argue *a fortiori* that if the lighter payload shows up better given this objective, then the case for it is all the stronger.

At some stage we must decide on a specific approach to the problem. The essence of the questions with which systems analysis is concerned is uncertainty, not only about economic, technical, and operational parameters – which can be serious but are to a large extent under our control and somehow appear limited – but also about future environments or contingencies. It is almost impossible to forecast what these might be, let alone to predict what an enemy might do about them. Hence, except in very narrowly defined problems, we must look for an approach to the men once described as "pipe-smoking, tree-full-of-owls types." And this may sometimes be the case; but typically it takes a lot of detailed individual research, conferences, and traveling by engineers, cost analysts, economists, political scientists, operations analysts, and other specialists to produce an analysis that makes a useful contribution.

The search for data can, of course, be endless, since in principle the uncertainties of most planning problems can never be completely eliminated. When should the theoretical analysis begin? What proportion of effort should be devoted to empirical research? D. M. Fort offers these suggestions:

> . . . the proper balance between theoretical analysis and fact-gathering depends on the problem. It is important, of course, to get the facts on the proper subject; a preliminary theoretical analysis can be very useful to this end, in pointing out what information is lacking and most needed. Much effort can be and often is wasted gathering the wrong data, for failure to do the necessary theoretical homework first. On the other hand, much effort is also wasted applying sophisticated analytical techniques to inadequate data, trying to make silk purses out of sows' ears. Physical experiments and data gathering in general are expensive; making plans and decisions in the face of uncertainty, even if aided by the best possible systems analysis, can also be very expensive. A proper balance may well call for much more emphasis on fact-gathering than has been customary.[6]

Expert opinion must be called upon when it is necessary to use numerical data or assumptions that cannot be based on theory or experience – when, say, we want to obtain something like an estimate of the guidance accuracy of our new missile in the presence of counter-measures that have been conceived in theory but have not yet been developed. Chapter 18 describes a method for doing this systematically.[7]

### *Evaluation*

In order to choose among alternatives, a way to estimate or predict the various consequences of their selection must exist. This may be as elementary as calling on the intuition of a single expert, but the more formal process of using a model or a set of models usually leads to better results. The role of the model in systems analysis is to provide a way to obtain cost and performance estimates for each alternative. Sometimes these estimates are obtained from a single over-all model – say, an elaborate computer program which combines into a single computation all the various submodels for determining dollar cost, reliability, lives lost, targets destroyed, and so on. At other times, consequences of different types are obtained separately by a wide variety of processes – gaming, computation, or political analyses.

Later, we will devote separate chapters to models in general and to

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[6] D. M. Fort, *Systems Analysis as an Aid in Air Transportation Planning*, The RAND Corporation, P-3293-1, March 1966, p. 10.

[7] The Delphi technique, pp. 435 ff.

three types common in systems analysis: simulations, war games, and scenarios.[8] Hence, the discussion here will confine itself to a few general remarks about the way models are used in systems analysis, especially as these models involve quantification and the use of judgment.

Consider our example of how to advise a decisionmaker on a substitute for the Minuteman. A typical military systems analysis such as this usually takes one of two forms. In the first, some level of military effectiveness (the objective) is fixed and an attempt is made to determine the alternative which will attain the desired effectiveness at minimum cost. In the second, the budget level is fixed and we seek to maximize effectiveness. Suppose we decide to take this latter approach.

To carry out the analysis, a specifically dated budget must be assumed and, using various models, the forces attainable with that budget must be worked out. This task, which is by no means simple, requires a cost model. In part, this model is constructed by measuring the purchase price not only of the various weapons and vehicles involved, but also of the whole materiel and manpower structure. The costs must take into account the entire system of utilization, extended over a period of time prolonged sufficiently to reflect the important factor of peacetime maintenance. It takes a great deal of research and sophisticated knowledge to cost a system that does not yet exist.[9]

Next, an environment and a mode of war initiation must be specified. Rather than base the analysis on a set of assumptions forced reluctantly from some consultant political scientist, an analytic scenario might be useful. Such a scenario starts with the present state of the world and shows, step by step, how one or more future situations might evolve out of the present one and how, in those situations, war might begin.

To carry on from here, a step-by-step procedure, called the campaign model, is used to work out what the war outcomes might be. Then, finally, some criterion or payoff function is used to weigh the various war outcomes and determine a preference ordering of the alternatives.

This process may break down at almost any stage. Some problems are so ill-structured and the cause and effect relationships so poorly understood that we cannot build a model with any feeling of confidence. When this is so, we cannot work out the consequences of adopting the various strategies or compare outcomes. The alternative is then to use a model which compares the salient characteristics of the possible strategies. This is the "consumers' research" approach, in which experts or "potential users" rate the alternatives. Again, of course, some way is needed to bring the various ratings together – a problem we have already looked at, but not

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[8] See Chapters 10–18.

[9] An example of this sort of cost analysis is given in Chapter 9.

when value judgments were involved. We will consider this in greater detail in a moment, for the same type of difficulty arises even when we can, in one sense or another, compute the outcomes.

It should be emphasized that, for many important problems, we are in fact unable to build really quantitative or even formal models. The most obvious function of a model is "explanatory," to organize our thinking. What counts, therefore, is not whether the model was mathematical or was run on a computer, but rather whether an effort was made to compare alternatives systematically, in terms as quantitative as possible, using a logical sequence of steps that can be retraced and verified by others.

Usually, we can go beyond this bare minimum, and although we may not be able, at least initially, to abstract the situation to a mathematical model or series of equations, some way can generally be found to represent the consequences that follow from particular choices. Simulation, for example – the process of imitating, without using formal analytic techniques, the essential features of a system or organization and analyzing its behavior by experimenting with the model – can be used to tackle many seemingly unmanageable or previously untouched problems where a traditional analytic formulation is at least initially infeasible. Operational gaming – that is to say, simulation involving role-playing by the participants – is another particularly promising technique, especially when it is desirable to employ several experts with varying specialities for different aspects of the problem. Here the game structure – again a model – furnishes the participants with an artificial, simulated environment within which they can jointly and simultaneously experiment, acquiring through feedback the insights necessary to make successful predictions within the gaming context and thus indirectly about the real world.

Getting back to our example, suppose there is general agreement (highly unlikely!) that the model accurately reflects the real situation and that the calculations are valid. Suppose further that, for a particular set of assumptions (about such things as the way war begins, the strength and disposition of the enemy forces, and so on), the expected or average "war outcomes" as computed by the model are those shown in Table 3.1:

TABLE 3.1

**Hypothetical war outcomes for three alternatives**

| Expected War Outcomes | Alternatives | | |
|---|---|---|---|
| | A | B | C |
| Number of Enemy Targets Destroyed | 80 | 100 | 150 |
| Hours to Destroy 50 Enemy Targets | 1 | 2 | 4 |
| U.S. Lives Lost (millions) | 20 | 25 | 50 |
| Cost to the Enemy to Cut His Losses by 50 per cent ($ billions) | 3 | 12 | 180 |

Of course, many other outcomes might have been computed or estimated from war gaming exercises that took other considerations into account – flexibility, contributions to our limited war capabilities, and so on. But given what we have, how does one decide which alternative to prefer? Fifteen years ago the rule was: Pick the system which destroyed the most targets for the given cost. Today we realize we must be interested in the other outcomes as well – some of which we cannot compute. One unrecommended way to determine a preference *a priori* is to use a payoff function which takes only the various numerical outcomes into account.[10]

A single decisionmaker would probably operate differently. He need only make up his mind, arguing with himself – thinking, for example:

> "C should be chosen. The potential threat it represents means that the probability of war will be reduced practically to zero and the cost to the enemy to counter it will collapse his economy."

Or, alternatively:

> "A is best. The primary purpose of these systems is to create a threat of unacceptable damage; 80 targets are as good as 150 for this purpose. C is too threatening; it leaves the enemy no choice but to attack."

In the usual case, there are a number of decisionmakers. The process changes accordingly, for what is needed is a collective judgment from them and the experts on whom they lean for advice.

Whenever possible, of course, this judgment should be "considered" judgment; that is, supplemented by inductive and numerical reasoning and made explicit. But it is judgment nonetheless.

How, then, might we apply group judgment to the problem of choosing one of the systems A, B, and C? We might seek a consensus by using one of several methods that allow us to pool the judgments of experts when faced with factual value uncertainty. The Delphi technique is a possibility.[11] Another is simply to ask each of our decisionmakers or experts to fill in an

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[10] For example, confining ourselves to the four war outcomes we have listed, we might say: Pick the system for which the product of the number of targets destroyed and the logarithm of the cost to the enemy, divided by the product of the number of lives lost and the time to destroy 50 targets, is greatest. Using this payoff, the analyst would reach these results:

A: $(80 \log_e 3)/20 = 4.4$
B: $(100 \log_e 12)/50 = 5.0$
C: $(150 \log_e 180)/200 = 3.9$

This indicates that B should be the choice. But the use of such a function is extremely arbitrary; it might be just as absurd to use the square root instead of the logarithm of the cost to the enemy. The values for A, B, and C would then be 6.9, 6.9, 10.1, respectively. Either payoff function would give a lesser weight to the cost factor than to the other factors involved, but by what logic can we choose such a function? This approach is never satisfactory unless there is a logical argument or empirical evidence to determine the form of the payoff.

[11] See pp. 435 ff. for a description of this method.

array such as the one illustrated in Table 3.2. After the experts had estimated the military worth of the various considerations relevant to the decision – using, say, a number between 0 and 10 – we could then work out a numerical measure.[12]

TABLE 3.2

**A framework for evaluating alternatives**

| Consideration | Rating of Alternatives | | |
|---|---|---|---|
| | A | B | C |
| Targets Destroyed | — | — | — |
| Time to Destroy 50 Targets | — | — | — |
| U.S. Lives Lost | — | — | — |
| Cost to Enemy | — | — | — |
| Intra-war Deterrence Capability | — | — | — |
| False Alarm Security | — | — | — |
| Flexibility | — | — | — |
| Growth Potential | — | — | — |

In addition to uncertainty as to the outcomes as listed in such a table, and moral or value uncertainty as to which combination of outcomes would be preferable, this problem also presents uncertainty as to the state of the world and the actions of the enemy. (This further complicates our problem, for we would have a display such as Table 3.1 for each contingency). But even if we went no further than to display systematically the opinions and judgment of a single decisionmaker for his own use, the exercise would be likely to help him. If the quantitative judgments of others are presented along with their arguments, they should be still more valuable, even though we might not make use of feedback to bring the various judgments more nearly to a consensus.

These, then, are some of the general notions the analyst cannot ignore. In a certain sense, specifically in their application to the problem of building models, they can be reduced to two heads: questions involving quantification or the treatment of uncertainty. Since almost every author in this book discusses uncertainty, we may content ourselves here with a simple example that points out what is meant by the explicit treatment of uncertainty. Its problems are, of course, intimately associated with those of quantification.

> A farmer must decide what crop or crops to plant without knowing whether the weather will be wet, moderate or dry. An analysis is performed to help him decide.

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[12] A very similar approach is advocated by Everett J. Daniels and John B. Lathrop in "Strengthening the Cost-Effectiveness Criterion for Major System Decisions," a paper presented at the October 1964 meeting of the Operations Research Society of America.

> A popular approach is employed in which the analysis is repeated in turn for each of the three distinguishable types of weather, in each case determining the best crop to plant for that type of weather. Considering all possible crops, it is found that for wet weather corn would be best, for moderate weather oats would be best, and for dry weather wheat would be best. The principal results presented to the farmer consist of the findings concerning the best crops in the three types of weather, the best yields achievable in each contingency (i.e., the wet-weather yield of corn, the moderate-weather yield of oats, and the dry-weather yield of wheat), and estimates of the probabilities of wet, moderate and dry weather. The implication is that the farmer ought to make his choice from the "preferred" crops, corn, oats or wheat, or perhaps a combination of these to provide some all-weather insurance.
>
> The farmer is not satisfied with the analysis, however. He points out that the analysis tells him what crop he should plant if he knew for certain what the weather would be, but he doesn't see how this helps him to decide what to plant when he doesn't know what the weather will be, except for the weather probabilities. He would like to know, for example, what will happen if he plants corn and the weather turns out moderate or dry, and similarly for the other crops. The analyst therefore prepares a two-way contingency table, showing for each of the three "preferred" crops the yields in wet, moderate and dry weather. Yields for various mixtures of these crops are also shown in the various types of weather. It is found that each of the three crops is rather narrowly tailored for that type of weather in which it is best, and gives disastrously poor yields in other types of weather. Oats, for example, gives poor yields in wet or dry weather, but very good yields in moderate weather. The farmer can insure against disaster by planting a mixture of corn, oats and wheat, thereby obtaining a fair overall yield whatever the weather.
>
> The farmer is still not satisfied, however. The contingency table does give him the information he wants on the three "preferred" crops, but he would like to see the same information for some other crops, even though they have been ruled out as "inferior" in the analytical optimization. The analyst obligingly expands the contingency table to show the yields of various other "inferior" crops in wet, moderate and dry weather. At this point it is noted that cane, which is inferior to corn in wet weather, inferior to oats in moderate weather, and inferior to wheat in dry weather, gives a "pretty good" yield in all types of weather, providing better all-weather insurance than can be achieved with any combination of the three "preferred" crops. This particular farmer, having a pronounced aversion to risk, decides that of all the crops he prefers the weather-yield pattern of cane over that of any other crop or combination of crops. Another farmer, looking at the same table, might prefer to take somewhat more of a chance on alfalfa, another "inferior" crop shown to give a rather good yield in wet or moderate weather but a poor yield in dry weather. Still another might prefer to take a greater chance on corn, but not necessarily because it was one of the "preferred" crops in the original analysis.[13]

The first approach described above, which determines which of the farmer's various options is "preferred" for each situation or specific set of assumptions about the uncertain factors, is far from uncommon in actual applications of systems analysis. It is useful in indicating some of the systems that merit consideration by the decisionmaker or planner. It can be worse than useless, however, if it leads him to limit his attention only to those "preferred" systems.

The approach that evolves toward the end of the example has the advantage of not ruling out systems that ought to be considered. It has

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[13] D. M. Fort, *Systems Analysis as an Aid in Air Transportation Planning*, pp. 12–13.

the disadvantage, however, of not ruling out very many systems at all, for it eliminates only those systems which are "inefficient"; that is, systems which are inferior or at most equal to other systems in *all* situations or for *all* assumptions about uncertain factors. Some means must be found to narrow the list further. This may require going beyond the bounds of strictly quantitative analysis, by such expedients as eliminating systems or uncertainties by direct application of the analyst's judgment or that of experts on whom he might call.

> Whatever approach is used in narrowing down the list of systems to be presented to the customer, the approach should be described as explicitly as possible. The presentation should include, among other things, a contingency table, showing for each system its performance and cost in each of the various relevant situations and/or for each set of assumptions about the uncertain factors. Digesting this information and using it in making decisions or plans puts a heavy burden on the decision-maker or planner, but it can't be helped. Systems analysis does not relieve the customer of the responsibility for facing the uncertain consequences of his decisions or plans; it can, however, help him face uncertainty with a better appreciation of the relevant considerations than he might otherwise have had.[14]

Why is quantification desirable? Some aspects of problems of choice in national security require numbers; others do not. When a quantitative matter is being discussed, the greatest clarity of thought is achieved by using numbers instead of avoiding them, even when uncertainties are present. Only in rare cases is it possible to make a convincing comparison of alternatives without a quantitative analysis.

> What is at issue here really is not numbers or computers versus words or judgment. The real issue is one of clarity of understanding and expression. Take, for example, the statement "Nuclear power for surface ships offers a major increase in effectiveness."
>
> Precisely what does that mean? Does it mean 10 per cent better or 100 per cent better? When that sort of question is asked a frequent answer is, "It can't be expressed in numbers." But it has to be expressed with the help of numbers. Budgets are expressed in dollars, and nuclear power costs more than conventional power. If nuclear power costs, say 33 per cent more for some ship type, all factors considered, then, no matter what the budget level, the Navy and the Secretary of Defense have to face the choice of whether to put the nation's resources into four conventional or three nuclear ships, or for a larger budget, eight conventional or six nuclear ships, and therefore whether by "major increase" is meant more than 33 per cent, about 33 per cent, or less than 33 per cent. Because the Secretary of Defense has to make the decision in these terms, the statement "major increase" is not particularly helpful. It must be replaced by a quantitative analysis of the performance of various missions, leading to a conclusion such as, "Nuclear power for surface ships offers something between X and Y per cent more effectiveness per ship. Therefore, $1 billion spent on nuclear powered ships will provide a force somewhere between A and B per cent more or less effective than the same dollars spent on conventionally powered ships.[15]

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[14] D. M. Fort, *Systems Analysis as an Aid in Air Transportation Planning*, p. 15.

[15] Alain C. Enthoven, Assistant Secretary of Defense (Systems Analysis), "Choosing Strategies and Selecting Weapon Systems," *United States Naval Institute Proceedings*, Vol. 90, No. 1, January 1964, p. 151.

Some variables are difficult to quantify, either because they are not calculable, like the probability of war, or because no satisfactory scale of measurement has yet been devised for them, like the effect on NATO solidarity of some unilateral U.S. action. This sometimes leads either to their neglect, for they tend to be ignored, or to their being recognized only by modifying a solution reached in fact by manipulating quantified variables. Thus, when the problem arises of using the model to recommend an action, the analyst may have trouble weighing these variables properly: the effect of the quantitative variables is built in, while that of the nonquantitative ones may be easily lost in the welter of qualitative considerations that must be taken into account.

As we have already seen, certain variables can be eliminated, either because they are irrelevant or trivial in their quantitative effects or because they have roughly the same effect on all the alternatives under consideration. The second explanation is the more important. Indeed, the fact that many variables fall into this category makes analysis possible. If the results were *not* insensitive to all but a relatively small number of variables, analysis would have to yield completely to guesses and intuition. *The point is that this insensitivity must be discovered.* Sometimes logical reconnoitering alone is sufficient, but usually analysis is required, possibly with arbitrary values assigned to the variables we are unable to calculate.

If nonquantitative variables are not to be neglected without mention or dismissed with some spurious argument, such as the one that they act in opposite direction and hence cancel out,[16] then how are they to be treated? The usual method is the one mentioned a moment ago – to attempt to take them into account through modification of the solution rather than to incorporate them into the model. But this in itself represents a particular method of quantification, for, by altering the solution to take account of the previously omitted variables, the analyst is implicitly valuing them. Since we nearly always have some insight into the range of values that a factor might take, we can, in many cases, assign it an arbitrary value and observe the effect on the solution.

In the general process of investigating a problem and gathering data about it, the analyst will have developed ideas of what considerations are likely to be most influential in determining the possible courses of action. To construct a model, he uses these insights – which actually represent crude preliminary models – and conducts pencil and paper experiments to illuminate their implications. Analysis, being iterative, is self-correcting; as the study goes on, early models are refined and then replaced, so that

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[16] It is not enough to know that two variables act in opposite directions; their quantitative impact must also be estimated.

the behavior of the relationships being investigated is represented with greater accuracy.

For most phenomena, there are many possible representations; the appropriate model depends as much on the question being asked as on the phenomena about which it is asked. A town can be modeled by a map if the question being asked is how to walk from A to B; but if the question is how to speed up the flow of traffic between the same two points, a much more elaborate model may be needed. The point is that there are no "universal" models – that is to say, no one model that can handle all questions about a given activity.

"Working" the model, trying out various strategies and concepts of operation, is the closest systems analysis comes to scientific experimentation. Deductions based on operating with the model frequently suggest new directions of effort. That is to say, starting with the relatively few parameters that characterize a system in terms of the model, it is sometimes possible to show that changing them would improve the performance of the system as measured by the model, which, in turn, might suggest corresponding improvements that could be made in the real system as it performs in the real world. In this way, working the model contributes to system design.

It is also important to go outside the model, to contemplate changes that violate its assumptions, and thereby perhaps achieve a better model. But whether or not one model is better than another does not depend on its complexity or computability, but solely on whether it gives better predictions. Unfortunately for systems analysis, but possibly fortunately for the world, this test is not usually an operational one when military problems are being considered.

### *Interpretation*

At this stage, not only does the analyst attempt to interpret his work, but so does the sponsor or the decisionmaker. Thus, the real world gets into the iterative cycle again, possibly to counteract its always imperfect mapping onto the model and, hopefully, to produce better answers.

As we remarked earlier, good criteria can only be found by working with the problem; that is, they cannot be developed *a priori*. Ends and means interact. Are the criteria good? What are the costs? What is the state-of-the-art? Are the objectives attained? Judgment must tell us whether we need to modify these things and run through another cycle or not.

Suppose the study has been done properly. Say the assumptions are reasonable, the chain of reasoning logical, the judgments as to the various inputs sound. This does not mean that the analysis is ended. As we have seen, the outcomes obtained from a model must be interpreted in the light of considerations which may not have been adequately treated by the model. Thus, in our example, the decisionmaker (or, for that matter, the systems analyst) may have established the requirement that a follow-on Minuteman worth considering have the capability to assure the destruction of, say, 95 per cent of a certain target list under a particular range of contingencies. But many questions occur. Perhaps the minimum cost of achieving this capability for all alternatives is too high; maybe the tasks of deterrence and limiting damage to the United States which we are trying to assure with our damage capability could be better done by spending less on strategic forces and more on air defense. The 95 per cent measure of effectiveness may be too high, or too low. Someone must translate the percentage of target destruction into its implications in terms of more meaningful criteria, such as the balance of military forces, the will to continue fighting, and the effect on our diplomacy. We can never know these things fully. For indicating the attainment of such vaguely defined objectives as deterrence or victory, it is even hard to find measures that point in the right direction. Consider deterrence, for instance. It exists only in the mind – and in the enemy's mind at that. We cannot use some "scale of deterrence" to measure directly the effectiveness of alternatives we hope will lead to deterrence, for there is no such scale. Instead, we must use such approximations as the potential mortalities that we might inflict, or the industrial capacity we might destroy. Consequently, it is clear that, even if a comparison of two systems indicates that one could inflict 50 per cent more casualties on the enemy than the other, we cannot conclude that this means the system supplies 50 per cent more deterrence. In fact, since in some circumstances it may be important not to look too threatening, we can argue that the system capable of inflicting the greatest number of casualties may provide the least deterrence!

The solution to a problem that has been simplified and possibly made amenable to mathematical calculation by drastic idealization and aggregation is not necessarily a good solution of the original problem. But even if the model and its inputs are excellent, the results may be unacceptable. The reason is obvious: Major decisions, in the field of military policy, are part of a political as well as an intellectual process. To achieve efficiency, considerations other than those of cost-effectiveness are important – discipline, morale, *esprit de corps*, tradition, and organizational behavior. The size, composition, location, and state of readiness of forces influence our foreign policy and the freedom of action we have. They also have a major impact on our domestic economy and public morale. The men who must somehow integrate these factors with the results of the study must necessarily deal with much that is nonquantitative, and their results may differ.

It is important for the user of analysis to distinguish between what the study actually shows and the recommendations for action the analyst makes on the basis of what he, the analyst, thinks the study implies. Some experienced and successful users of analysis hold even stronger views:

> Simply said, the purpose of an analysis is to provide illumination and visibility – to expose some problem in terms that are as simple as possible. This exposé is used as one of a number of inputs by some "decision-maker." Contrary to popular practice, the primary output of an analysis is not conclusions and recommendations. Most studies by analysis do have conclusions and recommendations even though they should not, since invariably whether or not some particular course of action should be followed depends on factors quite beyond those that have been quantified by the analyst. A "summary" is fine and allowable, but "conclusions" and "recommendations" by the analyst are, for the most part, neither appropriate nor useful. Drawing conclusions and making recommendations (regarding these types of decisions) are the responsibility of the decision-maker and should not be preempted by the analyst.[17]

When new minds – the decisionmaker's, for example – review the problem, they bring new information and insight. Even though the results obtained from the model are not changed, recommendations for action based on them may be. A model is only an indicator, not a final judge. While the analysis may compare the alternatives under a great many different assumptions, using various models, no one would expect the decision to be made solely on the basis of these comparisons alone – and the same would hold even if an immensely more complicated version of the study were to be carried out.

When should an inquiry stop? It is important to remember that, in problems of national security, inquiry is rarely exhaustive. Because it is almost always out of the question to collect – much less process – all the information that is required for exhaustive analysis, inquiries are partial, and the decisionmaker must get along without the full advantage of all the potentiality of systems analysis, operations research, and the scientific approach. Inquiries cost money and time; as we suggested earlier, they can cost in other values as well. They can cost lives; they can cost national security. This is not to say that some costs cannot sometimes be ignored; the point is rather that paradoxes arise if we allow ourselves to forget that almost all inquiries must stop far, far short of completion either for lack of funds or time, or a justification for spending further funds or time on them.

For these reasons, an analysis is usually far from finished when it is briefed to the decisionmaker or even when it is published. There are always unanswered questions that could be investigated further, even though the need for reporting requires a cutoff. And the decisionmaker's questions and reactions will usually involve an extension of the study.

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[17] Maj. Gen. Glenn A. Kent, "On Analysis," *Air University Review*, Vol. XVIII, No. 4 (May–June 1967), p. 50.

Since we must often give our advice before we are fully ready, we may be wrong on occasion. But one cannot do useful work in the field of defense analysis unless he is willing to accept uncertainty. If, in the judgment of the analyst and those who use his analysis, the alternative ranked highest by the criterion is good enough, the process is over; if not, more and better alternatives must be designed or the objectives must be lowered. Analysis is helpful in reaching a policy conclusion only when the objectives are agreed upon by the policy-makers. In defense policy in particular, and in many other cases as well, objectives are not, in fact, agreed upon. The choice, while ostensibly between alternatives, is really between objectives, and nonanalytical methods must be used for a final reconciliation of views. Although the consequences computed from the model may provide guidance in deciding which objectives to compromise, such decisions are not easily made, and judgment must in the end be applied.

## Chapter 4

# CRITERIA AND THE MEASUREMENT OF EFFECTIVENESS

L. D. ATTAWAY

*The central problems in the design of analyses to aid military decision-makers lie in selecting operationally useful objectives, measures of their attainment, and criteria. This chapter explores these problems. It attempts to show the relationship between costs, criteria, and objectives, and to point out common errors in their choice or use. It also shows the difficulties of definition and measurement which are introduced in going from simple decision problems concerning narrowly defined systems and operations to complex decision problems concerning broad defense systems, and provides some guidelines for proceeding in the broader context.*

### INTRODUCTION

This chapter has two aims: to show the relationship between costs, criteria, and objectives, and to point out some of the more common errors in their choice or use. It proceeds by first reviewing the various elements of a general decision problem and then discussing how they interact in a sequence of three examples, beginning with a rather narrow, well-defined problem of applied research, and continuing through a very broad, incompletely defined strategic problem. Examining this sequence of problems should provide insight into the techniques of measuring effectiveness, and some idea of the more difficult aspects of measurement. The discussion concludes by considering the character of the decision problem which remains after completion of such analyses.

### ELEMENTS OF ANALYSIS

E. S. Quade has already outlined, in Chapters 1 and 3, the major elements of the typical decision problem in systems analysis. For our purposes here, however, we will find it convenient to express one or two of them somewhat differently, in order to avoid a common ambiguity of terms. Thus, in the following list of the elements of decision problems, we depart from Quade's usage by isolating something that we call an *effectiveness scale*, which, in turn, we use in defining *effectiveness*:

| | |
|---|---|
| Objective: | What we desire to achieve |
| Alternatives: | Competitive means for achieving the goal |
| Costs: | Expenditures to acquire each alternative |
| Effectiveness Scale: | Scale indicating degree of achievement of goal |
| Effectiveness: | Position on effectiveness scale assigned to each alternative (by measurement) |
| Criterion: | Statement about cost and effectiveness which determines choice |

The rationale of this change is straightforward.[1] Clearly, without a scale of effectiveness on which the position of an alternative will indicate its ability to achieve the goal, evaluation of alternatives would be impossible. The scale is a yardstick, along which we place our alternatives by means of some analytic or subjective technique of measurement; this position indicates the alternative's effectiveness. Now, people sometimes want to substitute the term "criterion" for "effectiveness scale," or replace "scale of effectiveness" with "measure of effectiveness." But to keep the following remarks unambiguous, and preclude some of the semantic difficulties often met in similar discussions, we will use the terminology and definitions just given.

Our breakdown of the decision problem is general enough to apply to problems as different as selecting a new aircraft engine; choosing the best operational mode for an interceptor force (for example, close versus broadcast control); designing a new interceptor aircraft force; allocating a budget between civil defense and active defense; and, finally, determining the size of the strategic budget and how it might best be distributed between offense and defense.

### AN EXAMPLE: SELECTION OF A NEW AIRCRAFT ENGINE

As an example of how these elements of analysis figure in a relatively narrow decision problem, let us consider the selection of a new aircraft engine, and assume that the *objective* is simply to increase engine performance. Then the *alternatives* are obviously the various possible engine types that achieve this objective by such means as exotic fuels or novel design. The *costs* would be of two general kinds: the total capital resources (such as manpower and research facilities) that must be allocated to the research, and the time required to achieve a successful prototype. In this simple case, the *effectiveness scale* relates directly to the objective, and might be taken as the difference between the specific fuel consumption typical today and that achieved by further research, for fixed engine weight. The *effectiveness*

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[1] Moreover, it implies no contradiction with anything Quade has said.

of a particular alternative engine type would then be its estimated reading on this scale. The greater the difference, the better the engine, since we desire to decrease the specific fuel consumption by research. In general, the amount of improvement will depend upon the amount of effort expended upon research, so that estimated costs and effectiveness might be related as shown in Fig. 4.1.

Such different levels of performance might result from a situation that H. Rosenzweig will discuss more fully later,[2] in which alternative 1 corresponds to a very conservative improvement over operational engines, and alternative 2, to a larger state-of-the-art advance.

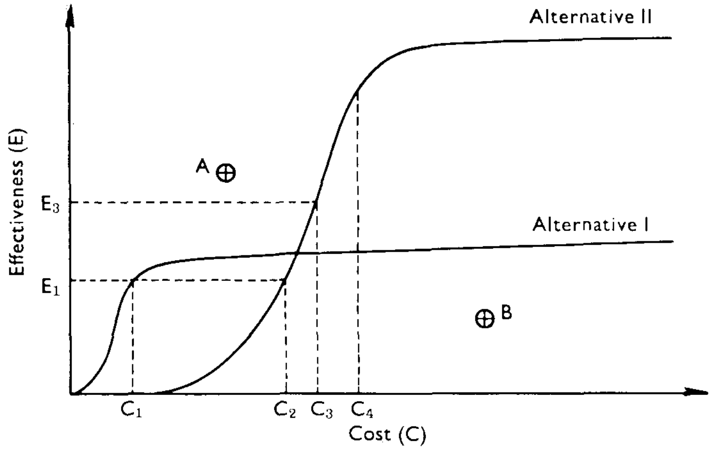

Fig. 4.1 – Cost and effectiveness

Note, however, that even if we assume that both these alternative research programs can be completed on time and are subject to essentially the same amount of uncertainty, we still could not decide between them. What is missing is some knowledge of why the improved performance is needed. Thus, although alternative 1 achieves only a modest level of effectiveness ($E_1$), it does so at one-third the cost of alternative 2. If the level $E_1$ is adequate, why not select alternative 1 and thereby minimize cost? Indeed, quite often cost will be limited by decree to some level such as $C_2$, in which case alternative 1 is the obvious choice. On the other hand, the goal of the research may be to achieve some minimal new level of effectiveness, such as $E_3$, no matter what the cost. Then alternative 2 is obviously the choice.

The point to be made is that, in general, it is not possible to choose

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[2] In Chapter 6.

between two alternatives just on the basis of the cost and effectiveness data shown in Fig. 4.1. Usually, either a required effectiveness must be specified and then the cost minimized for that effectiveness, or a required cost must be specified and the effectiveness maximized. Clearly, the results of the analysis of effectiveness should influence the selection of the final criterion. For example, if $C_3$ is truly a reasonable cost to pay, then the case for $C_4$ is much stronger, in view of the great gains to be made for a relatively small additional investment. As a matter of fact, this approach of setting *maximum* cost so that it corresponds to the knee of the cost-effectiveness curve is a very useful and prevalent one, since very little additional effectiveness is gained by further investment.

### *Overspecification of Criteria*

On the other hand, both required cost *and* effectiveness should not be specified; this overspecifies the criterion, and can result in asking for alternatives that are either unobtainable (point A in Fig. 4.1) or underdesigned (point B in the same Figure). An extreme case of criterion overspecification is to require maximum effectiveness for minimum cost. These two requirements cannot be met simultaneously, as is clear from Fig. 4.1, where minimum cost corresponds to zero effectiveness, and maximum effectiveness corresponds to a very large cost.

### *Maximizing Effectiveness/Cost*

Somewhere in the middle are criteria that apparently specify neither required cost nor effectiveness. One which is widely used calls for maximizing the ratio of effectiveness to cost. This seems to be a workable criterion, since, in general, we want to increase effectiveness and decrease cost. Nevertheless, as we can see by examining Fig. 4.2, it has a serious defect. Since the effectiveness-cost ratio for either alternative is simply the slope of a line drawn from the origin to a given point on the curve for that alternative, and since, in this example, the ratio obviously takes on a maximum at the knee of the curve, our choice between the two alternatives seems to be settled at once. Thus, alternative 1 is clearly preferred with this criterion. However, if $E_3$ is the minimum level of effectiveness acceptable from a research program, then alternative 2 is the obvious choice. The point to be made here is that unless the decisionmaker is completely unconcerned about *absolute* levels of effectiveness and cost, then a criterion such as this, which suppresses them, must be avoided.

Theoretically, it is possible to escape this need for specifying either the required cost or effectiveness by expressing cost and effectiveness in the same units, such as dollars or equivalent lives saved. For if this can be done, then it is possible to subtract cost from effectiveness, and take as the crite-

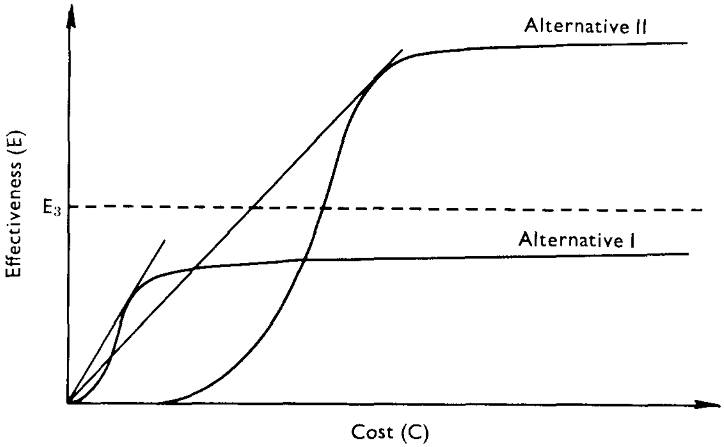

Fig. 4.2 – Effectiveness/cost ratio

rion the maximization of this difference. But seldom, if ever, can cost and effectiveness be expressed in similar units, and we may assume that the earlier description of a criterion applies.

*Dominance*

Infrequently it happens that selection between alternatives is easy. An extreme case of this is shown in Fig. 4.3, and occurs when an alternative

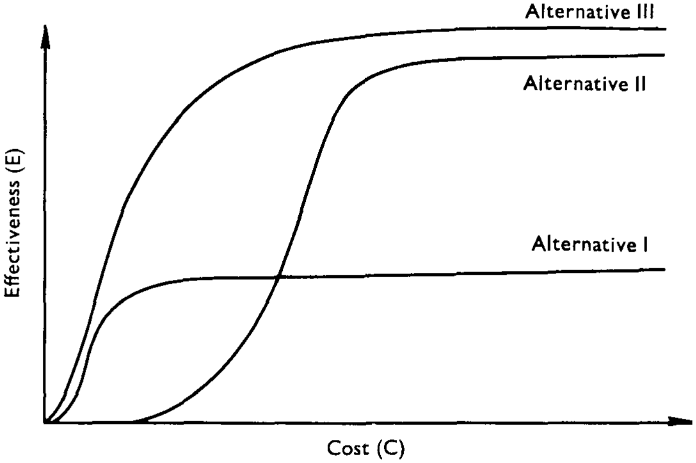

Fig. 4.3 – Dominance

such as 3 is more effective than any other at every cost. In such a case it is clearly advantageous to select alternative 3, which is said to *dominate* alternatives 1 and 2 at all levels of investment and effectiveness. Note that it is still not permissible to overspecify the criterion and require maximum effectiveness for minimum cost. For the situation of dominance only permits us to select alternative 3; minimum cost still corresponds to zero effectiveness for alternative 3, and so forth. Even though dominance designates alternative 3 as preferred, the required level of effectiveness must be specified before the preferred level of investment can be selected.

In this example of propulsion research, as in many others in advanced research or specific component design, the goal has been simple and obvious. Further, in such cases an appropriate scale of effectiveness is usually obvious and related directly to the goal. Finally, the measurement of effectiveness (that is, the location of an alternative upon that effectiveness scale) is straightforward in such cases. Since the example at hand will be discussed by H. Rosenzweig in some detail,[3] we can conclude our discussion of it here, and pass on to the more difficult, but perhaps more interesting, questions the analyst must face in identifying goals, selecting scales of effectiveness, and performing the measurement of effectiveness for some of the other problems which were mentioned earlier.

## A SECOND EXAMPLE: CHOICE OF OPERATIONAL MODE FOR INTERCEPTORS

The second of these problems deals with selecting the best mode of operation for an interceptor force: close control versus broadcast control. Close control is defined as that mode of operation in which individual interceptors rely heavily upon vectoring commands generated by an air surveillance system external to the aircraft. Broadcast control is that mode of operation in which vectoring commands are generated within the individual interceptors, based upon air surveillance data provided by an area surveillance system external to the interceptors.

### *Selection of a Scale of Effectiveness*

The ultimate goal of an interceptor force is to prevent damage to the United States, and a useful scale of effectiveness must relate to this ultimate goal in a meaningful way. In this case, there is a hierarchy of potential scales of effectiveness, which includes, for example, the probability of a bomber kill per interceptor attempt, average number of bomber kills per interceptor sortie, total number of bomber kills in a campaign, and number of U.S. survivors in a complete campaign. Which is most useful will depend upon many factors. A general guideline is to choose the narrowest goal possible in order to minimize analytic effort.

The usefulness of these scales depends upon what part of the interceptor force is fixed. If the choice between close and broadcast control is to be

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[3] In Chapter 6.

made for an existing interceptor force for which aircraft types and numbers, aircraft and ground systems, and deployment are all fixed, then a simpler scale may suffice. Thus, we might expect that maximizing the average number of kills per interceptor sortie will also minimize the damage to the United States in a campaign. But the probability of a bomber kill per interceptor attempt is too narrow an effectiveness scale to use, for modern interceptors are capable of several attempts per sortie, and using this scale might lead to selecting an alternative which maximizes first-attempt performance at the expense of wasting most of the aircraft's sortie endurance and armament.

As long as the choice is between types of control, the average number of kills per interceptor sortie should be an adequate scale. On the other hand, including just one other aspect of the interceptor force in the choice can require the use of an even broader scale of effectiveness. For example, if the mix of interceptor types is allowed to vary, and the decision problem is to choose the preferred mix *and* control mode, then a scale such as the total number of bombers killed per campaign must be used. For in this case, the use of the narrower scale of average kills per interceptor sortie could lead, for example, to selecting a force of interceptors and mode of control which maximizes kills per sortie in a way that simultaneously reduces the total number of sorties, thereby reducing the total kills per campaign. The correct selection entails the use of an effectiveness scale that correctly relates to the ultimate goals of air defense, such as the total number of bomber kills per campaign.

If the choice is broadened further to include the number of aircraft and their mix and deployment, then an even broader effectiveness scale must be employed, such as U.S. survivors of a campaign. For the ability of an interceptor force to prevent damage to the United States depends upon the geography of the target system and the force deployment relative to the target system. In a choice involving deployment, the effectiveness scale must reflect that factor correctly. The number of bomber kills per campaign does not, since its use might lead to accepting a deployment which effects more bomber kills than a second deployment, but which permits greater damage to the United States than does that second deployment.

Selection of a scale of effectiveness is often a difficult job, requiring understanding of the problem structure and invariably calling for compromise among the several factors of the real world and the analysis. Unfortunately, about the only general guidance one can give is to select scales of effectiveness which reflect the essence of the problem at hand and simultaneously make the measurement of effectiveness as simple as possible. We have just considered the need for reflecting the "essence" of the problem; let us now turn to the measurement aspect.

*Measurement of Effectiveness*

In the measurement of effectiveness, as in the selection of the effectiveness scale, the means of measurement should reflect the essence of the problem and make measurement both feasible and as easy as possible. The aim is to obtain a quantitative relationship between cost and effectiveness, similar to that which we found for the engine research example (see Fig. 4.1). The more factors which are allowed to vary, or which are to be optimized, the more difficult the measurement, since the technique must then adequately represent the appropriate relationships between the several varying factors. And the dependence of effectiveness upon each such variable must be spelled out, which increases exponentially the number of cases which must be "measured." In short, fixing most factors permits the use of a narrower effectiveness scale, such as total bomber kills per campaign rather than damage to the United States, which is much simpler to calculate and therefore requires vastly less labor. Therefore, in our interceptor control problem, it will be easier to measure the effectiveness of close and broadcast control for the situation in which all the characteristics of the interceptor force are fixed.

The task of measurement can be simplified still more, however, since even for a force completely specified as to aircraft types and numbers, aircraft and ground systems, and deployment, there are many ways of achieving close and broadcast control. Clearly, it would be desirable to discover and then compare only what we think are the best ways of achieving each. This means, of course, that the final measurement of effectiveness of our two alternatives would then rest upon a previous analysis which selects the best method in each case. Such an analysis would investigate the many aspects of the defense system which, in the ultimate analysis, we have just taken as fixed. It would also have to consider the nature of the enemy's operational force and what he chooses to do with it. And if the enemy is permitted to attack defenses, then the resulting variation in the characteristics of the defense forces would also have to be included in the analysis; in effect, the mix and deployment of aircraft types and the amount and ability of the ground systems might, at some point in the analysis, be variables because of possible enemy actions against them.

A prior analysis such as this for finding the best way of achieving close control is usually designed to provide a parameterized estimate of the best performance of an interceptor as a function of what the enemy does in fact do. For example, the product might be in the form of the probability of a bomber kill per interceptor attempt as a function of bomber stream density, altitude and speed, bomber radar and IR cross section, and residual ground environment performance. The aim is to provide a generalized estimate of the performance of the best operation as a function of the specific character of the actual conflict. This estimate, which would involve operational and experimental data, technical extrapolation of equipment performance, and mathematical modeling of the dynamic interceptor-bomber encounter, could then be used to evaluate many specific possibilities.

In a larger sense, the objective of such analysis is to place the final estimate of performance upon as fundamental a basis as possible, in terms of components and operations which have physical and operational meaning, and to provide an understanding of the accuracy of such estimates. To go into greater detail about how this is done would be inappropriate here, and, in any case, the point that should be emphasized is that such analysis is an essential, irreplaceable part of all systems analysis if it is to be truly meaningful.

Assuming, therefore, that earlier estimates of performance for the best form of close and broadcast control are in hand, it is possible to measure the effectiveness of the two alternatives. In some cases, these estimates themselves might comprise such an evaluation. Usually they do not – at least not in terms of an effectiveness scale such as the average number of bomber kills per sortie – because they do not integrate the operational factors appropriately. For the average number of bomber kills per interceptor sortie depends upon such things as the actual density, altitude, and speed of a bomber stream and the number of interceptors that actually penetrate the stream – which, in turn, depends upon where the interceptors are located, which targets are attacked by how many bombers, how much warning is available, and many other *operational* factors. Thus, some technique is needed for reflecting these operational factors in the estimation of the average number of kills per sortie. This might take the form of a map exercise in which interceptors are actually deployed and then committed against attacking bomber streams, duels are fought on paper or in a computer, and a final over-all campaign estimate is made of the average number of kills per sortie.

### *Selection of an Alternative*

This analysis must be performed for each significantly different but important case of enemy force, tactic, and competence. The final output might be of the form we saw earlier in Fig. 4.1, although each important case would, of course, have its own curves. Given such results, a criterion for use *in a particular case* would function as we noted before; that is, if one alternative were dominant at all levels of effectiveness and cost, it would be the obvious choice; if not, then either required cost or effectiveness would have to be specified before a decision could be reached. A criterion for use *across the cases* is a more difficult matter, which we will postpone until later, except to note that if either alternative is dominant across all cases then the decision is again straightforward.

This example has been discussed in detail in order to emphasize the need for reflecting in an effectiveness measurement those factors that are important *to the decision under consideration.* The point is that the particular questions we have considered are questions that must be considered in order to understand close versus broadcast control. Such detailed handling of these particular components is possible only because the problem is restricted to the narrow question of type of interceptor control. If a broader question is addressed, such as the choice between manned interceptors and local defense, or between civil defense and active defense, then the same detail may be possible, but *only relative to a higher level of system component.* That is, to analyze such broader problems, it is necessary to *suboptimize* and *aggregate.*

### *Suboptimization*

When, as in the preceding example, we simplify the problem of selecting an alternative by completely fixing certain characteristics that might, in fact, vary, the selection that results is called "suboptimum." It is suboptimum because we could usually do better if we allowed some or all of these characteristics to vary simultaneously, and made our selection from the resulting large set of possible mixes. Clearly, however, suboptimizations must be performed often and widely, since it is both necessary and permissible to make many decisions independent of each other. For example, it should be possible to design ballistic missiles independently of COIN aircraft, and ballistic missile defense techniques independently of interceptor ordnance. However, care must be taken not to overdo suboptimization. For example, airborne ordnance and fire control systems must be designed with due attention to the ground environment, or else vectoring accuracy and airborne radar performance can end up badly incompatible.

### *Aggregation*

Suboptimization permits the design of various components, such as wheels, engines, and ordnance, to be fixed. They can then be represented by a single over-all component, such as an aircraft; that is, we can then "aggregate" components into larger systems. Without this ability to aggregate, we could not study problems embracing many components, and the level of aggregation is an important aspect of any analysis.

For example, in the discussion of interceptor control, the level of aggregation did not go beyond such operational abstractions as these:

Deployment
Availability rate

Payload
Flight characteristics (speed, range, altitude, loiter)
Air-to-air detection probability
Probability of converting detection to bomber kill

But if the object of study were command-control of a controlled central war, then the relevant systems might be abstracted at a much greater level of aggregation, as in this list:

The national command
CINCSAC
CINCNORAD
CINCEUR
SHAPE

On this second level, manned interceptors would still be of interest, but they would be only one subsystem among many in a highly aggregated operational abstraction labeled "CINCNORAD." So manned interceptors might be represented by total kill potential and cost, a highly aggregated representation. However, if the broader analysis is to be truly meaningful, such aggregation must rest upon valid analysis (including appropriate suboptimization) of subsystems of the kind we have considered here in talking about interceptor control. This broader analysis, such as evaluating command-control of central war, will often have just as much detail as did the interceptor control example, but it will handle an equal number of major components at a higher level of aggregation.

### A THIRD EXAMPLE: ALLOCATION OF A STRATEGIC BUDGET

Thus, as we go from narrower decision problems to broader, more inclusive ones, we are actually going from many specific component studies to their synthesis. This synthesis, and the difficulties of dealing with many plausible future conditions of the world, are perhaps the most challenging problems in systems analysis today. We shall address them next, by discussing the last problem on our list: that of selecting the size of the strategic budget and allocating it between offense and defense. An obvious difficulty with such a broad problem is the magnitude of the analytic effort needed just to uncover all its facets, much less treat them thoroughly. We are not without tools for this task, however, and the first of them is, as always, definition. What are our goals?

### *The Definition of Goals*

In discussions of our strategic forces, it is generally recognized that the deterrence they provide does not apply to the entire spectrum of possible conflict, but only to those enemy actions provocative enough to warrant our involvement in a nuclear exchange and all that it entails. For example, our strategic forces should provide direct deterrence against attacks upon the United States or Europe, but only indirectly affect situations such as Vietnam. If, then, we restrict our attention to that part of the conflict spectrum which involves nuclear exchange between the United States and an enemy, we can say that the goal of the strategic forces is threefold:

> First, to deter direct attack upon the United States by guaranteeing that sufficient strategic forces will survive to inflict upon the attacker an unacceptable level of damage;
> Second, to limit damage to the United States should deterrence fail;
> Third, to prosecute the conflict to a conclusion favorable to the United States.

Another possible sub-goal, not obviously attainable, might be:

> Fourth, in certain situations to strike enemy military forces first with sufficient offensive force that the U.S. air and missile defenses can then limit to an acceptable level U.S. damage from the enemy's responding strike.

We thus see that an over-all strategic goal is actually a set of *multiple goals*, having to do with damage to the United States, damage to the enemy, prosecution and termination of a conflict, and the destruction or preservation of military forces.

Further, these goals are only *proximate*, in that they represent in only a suggestive fashion the true goal. For example, we all recognize that deterrence, to be credible, must rest upon our ability to damage the enemy as well as limit damage to our own country; but we are forced to handle these two goals almost independently of each other.

Also, these goals are *dissimilar*, since their achievement cannot be compared in equivalent units. For example, we simply cannot equate industrial damage and mortalities.

Finally, these goals can be *conflicting*, in that trying to achieve one may reduce our ability to achieve another. For example, expenditures devoted to damaging enemy industry conflict with expenditures to defend our cities, in that both compete for precious resources. Then, because their achievement must be measured in dissimilar units, these goals cannot be balanced against one another directly, but only subjectively.

In short, any idealized strategic goal must be replaced by multiple, proximate, dissimilar, and often conflicting goals. Therefore, the definition of effectiveness, and its measurement, can be made only in relation to these kinds of limited goals. The resulting decision problems can be very difficult. For example, consider two strategic systems – that is, alternatives – which have the performance indicated in Table 4.1. Is it better to buy alternative

1, which successfully limits damage to the United States, but with a rather low level of deterrence, or alternative 2, which is less effective in limiting damage to the United States, but presents a greater deterrent?

TABLE 4.1

**The performance of two possible strategic systems**

| Alternative | Population Surviving (%) | |
|---|---|---|
| | United States | The Enemy |
| 1 | 95 | 85 |
| 2 | 70 | 30 |

It is clear that such decisions are in the province of the decisionmaker proper, not the analyst, and that they must be subjective. Systems analysis should remove as much subjectivity from the decision as is legitimate – no more, no less. By no means should the basic nature of the decision portrayed in Table 4.1 be hidden or analytically camouflaged; that is, the decisionmaker should be left the job of balancing damage limitation against deterrence. Adequate professional guidance should be sought by the ultimate decisionmaker in balancing these conflicting goals, since no analysis can substitute for expert military, political, or scientific insight.

### *Limitations of Effectiveness Scales*

A large part of the difficulty of having to base a decision on results like those given in Table 4.1 arises from the effectiveness scale used – that is, population surviving. But the need to use such crude scales is unavoidable, in part because at this time we simply do not know enough about the internal processes of the principal elements of the United States to evaluate how they would be affected by varying degrees and kinds of damage. In fact, to date we can handle in our analyses essentially only the physically measurable external attributes of the United States. For example, we can reflect population in its many physical aspects – number, location, occupation, age, sex, dwelling, and so on – and we can also estimate the effects that a direct attack might have on these attributes. Similarly, we can reflect certain external aspects of industry, agriculture, the military, utilities, and so forth. But when it comes to estimating the impact of damage upon the ability of any such element to pursue its fundamental goals by means of its internal processes, we are generally without adequate tools of analysis.

The results are several. First, in measuring the effectiveness of an alternative in preventing damage to the United States, it becomes necessary to specify effectiveness scales for each of the principal elements – social, economic, military – of the U.S. complex. Second, these scales, no matter how carefully defined, must always turn out to be proximate, in that they will represent the effectiveness of an alternative to reduce damage in only a suggestive fashion. For example, when we consider limitation of damage to U.S. society, we are forced to use effectiveness scales such as population surviving or radiation levels following the conflict. We are hard put to handle such a sophisticated effectiveness scale as the ability to regain our 1960 subsistence level. Third, these scales are likely to be dissimilar, in that they will probably be expressed in units that are not equivalent. For example, population surviving and industrial floor space remaining intact might be used as effectiveness scales for the social and industrial elements, respectively. However, they cannot both be expressed in the same units, since we cannot equate a death to some amount of floor space. Fourth and finally, such scales will be conflicting, in that trying to do well on one tends to decrease the ability of an alternative to do well on another. For example, population surviving and industrial floor space surviving are conflicting when a defense mixture of active defense and fallout shelters for fixed cost is considered. For money spent on fallout shelters to save lives is spent at the expense of buying active defense, which saves both lives and floor space.

In brief, the situation for effectiveness scales is somewhat like that for goals, and leads to similar difficulties for the decisionmaker. For instance, consider two alternatives which have the performance shown in Table 4.2. Is it better to buy alternative 1, which preserves almost all the population but apparently with little provision for future subsistence, or alternative 2, which preserves a more modest fraction of the populace but with greater provisions for the future?

TABLE 4.2

**Hypothetical performance of two other strategic systems**

| Alternative | Population Surviving (%) | Basic Industrial Floor Space Surviving (%) | Agricultural Acreage Surviving (%) |
|---|---|---|---|
| 1 | 95 | 40 | 20 |
| 2 | 75 | 75 | 75 |

This trend towards expressing over-all effectiveness in terms of a number of very simple, but highly specific scales is contrary to the need to select scales broad enough to integrate the effects of dissimilar subsystems into an over-all effect. For example, in the strategic problem we are considering, it is not possible to use as scales the expected number of bomber kills per interceptor sortie and the expected number of re-entry bodies destroyed per ABM engagement. In order to use the output of the analysis as an aid to decision, a higher level scale of effectiveness is needed, such as population surviving, so that the contribution of the two subsystems can be combined. This, in turn, raises the question, Is it really possible to combine performance estimates for dissimilar systems, such as ABM and manned interceptors, inasmuch as the estimates usually differ markedly in accuracy and reliability? We will return to this problem a little later.[4]

### *Alternatives in an Uncertain Future*

If we assume that in our decision problem – that is, selecting a preferred strategic budget size and dividing it between offense and defense – we are looking to the future when a diverse menu of strategic systems will be available, we might then be considering the various systems shown in Fig. 4.4.

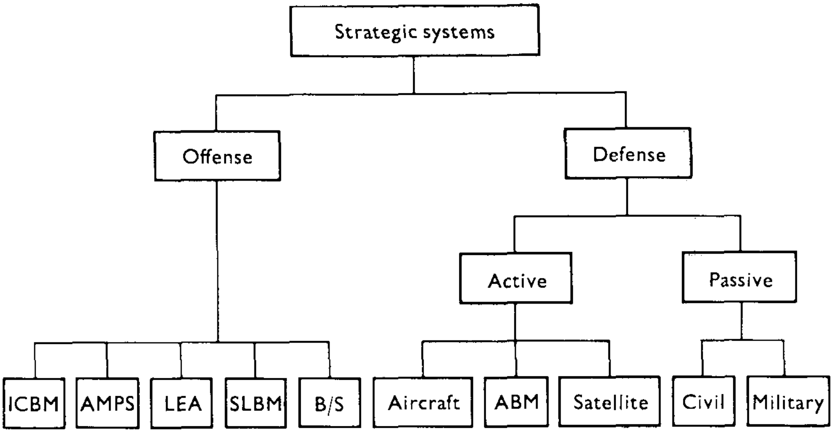

Fig. 4.4 – Strategic choices

The choice of an alternative in this problem is considerably more complex than in those we considered earlier. In this case, an alternative is identified by the amount spent in each lower box of Fig. 4.4 and a detailed specification of just how each amount is spent. The task for measurement is then to assign, to each such set of specifications, a value on each effectiveness scale being used. But each total budget can be spent in literally an infinite number of ways on the various systems. And since, as in the earlier examples, we want to spend each budget on these individual systems in the best way possible, each system considered must be subjected to analy-

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[4] It is also discussed by H. Rosenzweig in Chapter 6.

ses which, like those discussed earlier, are designed to select its best form. If this could actually be done, then even in this complex problem we might be able to plot cost and effectiveness as we did earlier. But now each cost would refer to a different optimal alternative – that is, to a different specification of how the budget is best spent on the different systems (Fig. 4.5). Further, the best allocation for a particular system will usually depend upon the amount and manner of spending on other systems, as well as upon various factors, such as the threat, which are not under the control of the decisionmaker. We might explore this aspect of analysis a little.

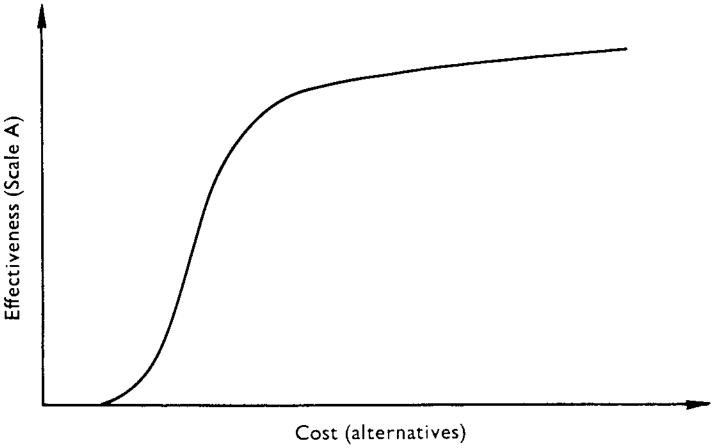

Fig. 4.5 – Effectiveness/cost for a series of alternatives

To do so, consider the ABM component of a possible defense system. In designing an ABM system, we would first like to resolve many uncertainties about the world in which it is to operate, such as these:

*Uncertainties about the Enemy*
  Tactics
  Technology (choice, level of achievement, quality)
  Force size
  Strategy (e.g., kind of war)
*Uncertainties about the United States*
  Technology (level of achievement, quality)
  System performance

Clearly, however, such matters are always largely unknowable, and only the last two are partly under our control. Let us look at each of them.

By "enemy tactics" is meant the detailed manner in which the enemy employs his forces. Will he apply ballistic missiles so as to saturate our

ABM? Will he use precursor attacks against defenses? Will he be smart, aggressive, operationally mature, or stupid, backward, inept?

As we all know, almost any level of technological sophistication and quality can be assigned to a *future* force. To what levels should the enemy be advanced in our design for ABM? Will he possess high-quality reentry decoys? Electronic countermeasures? Advanced payloads?

The difficulty of defense is determined to a great extent by the size of the enemy's force. What he lacks in quality he may recover in quantity. Offensive force size determines needed attributes of ABM, such as rate-of-fire, total kill potential required, and extent of deployment.

The strategy pursued by the enemy can dominate all the preceding factors. For example, if he chooses to fight a controlled war, then force size allocated per hour will be significantly smaller than otherwise, which, in turn, should reflect upon ABM design.

"Level and quality of technological achievement" will mean for the United States roughly the same kinds of things as we noted for the enemy.

The last item in the list, "system performance," can be defined in the following way. If we have a set of assumptions about the preceding enemy attributes, and an assumed level of achievement and quality of United States technology, then a "best" United States ABM system, as "best" was used before, can be designed to match those assumptions. Then to perform the job of measurement it would be necessary to find some method of expressing that basic system in terms of operationally recognizable units such as a battery – units which could be used in operational models especially designed to integrate the various weapon system effects and to reflect the operational aspects of the problem. The basic operating performance of these units would be described by such factors as these:

Battery interception rate
Decoy discrimination rate (per battery)
Probability of kill
Number of interceptor missiles per battery
Battery hardness

The resulting set of values for these various factors will then be the "system performance." These performance figures, however, are never really known; they can only be estimated. Further, they cannot be estimated with equal accuracy; some will be pinpointed, and others will possess wide ranges of uncertainty. Moreover, they can only be estimated after such uncertain aspects of the world as those listed earlier have been specified.

Now, these six factors – enemy tactics, technology, force size, and strategy, and U.S. technology and system performance – determine the state of the world within which the effectiveness of each alternative is to be measured. Since we can visualize many possible future worlds, each significantly different in some of these six factors, we must design an ABM system for each important possible world, in order to understand fully the ABM problem. We can call each combination of these six factors a *contingency*.[5] Fortunately – given a reasonably defined contingency – we are usually able to design what might be called a "rubber suboptimization": a system fixed except for certain attributes, such as rate-of-fire or discrimination rate, which can then be specified as a function of cost. Rubber designs are needed to handle such difficulties as variations in defense deployment and enemy tactics within a contingency, as well as problems met in cross-contingency analysis. The product of such suboptimized design will then be a set of numbers, or a set of ranges of numbers, for basic performance factors of the sort listed a moment ago.

In addition to these characteristics, we would also have the ICBM described as to such items as CEP, payload, availability, and time to target; the manned interceptors described as to analogous factors; and so forth. That is, we need a set of *component studies*, each addressed to suboptimized system design within each of a set of contingencies. Such a component study, spanning all the important contingencies, is needed for each principal weapon or support system we might consider including in an alternative. Individually, these studies will differ markedly, as we noted before, in the accuracy and reliability of their estimates of best system performance. Together, however, they should provide a reasonably close appraisal of that accuracy and reliability, so that these shortcomings can be appropriately reflected in the measurement of effectiveness, as well as in the final decision.

No alternative is completely specified until each system is spelled out as to number of basic units, deployment, and so forth. However, the best such specification for manned interceptors, for example, can depend upon a similar one for local air defense, ABM, or both. For if we defend some cities only against ballistic missiles, and others only against manned bombers, we leave ourselves vulnerable to an obvious enemy tactic; if we defend against manned bombers with local defense only and provide no fallout shelters or area defenses, we leave ourselves vulnerable to fallout attack from weapons delivered just outside the local defenses. Such interdependencies also exist between allocations of offense and defense, and are a difficult part of the analysis. Their main effect is twofold. First, they limit the amount of suboptimization that can take place within a subsystem, independent of the other subsystems. Second, they give rise to the need

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[5] The contingency problem is so central to the difficulties of systems analysis today that it needs careful development. As a matter of fact, most of the tried and true techniques of systems analysis are applicable only *within* a given contingency, and it is the need to handle analysis *across* many contingencies that gives rise to many current difficulties.

for a *synthesis* of the component studies, a synthesis that will result in an over-all strategic system – that is, alternative – which combines the individual subsystems in some best fashion. This need, in turn, prescribes that the output of the component studies will be most useful if it is parameterized.

This synthesis requires trading off the effectiveness of one subsystem for that of another, in order to achieve a best mix. For example, civil defense appears a better buy for initial investment than additional active defense, but a decision mechanism for determining the level of each is required. In such a process, differences in the accuracy and reliability of the results of the component studies must be recognized and taken into account. At least two means are available. The first is simply to treat an uncertain parameter as a contingency variable, and assign it an appropriate value for each contingency. The second is to perform *sensitivity analysis*. In this technique, the uncertain parameters are varied over their likely ranges to ascertain the sensitivity of the results to their actual value. If the sensitivity is slight, then a "typical" value of the uncertain parameter can be used throughout with little error. If sensitivity is great, then this analysis can be used to select the preferred values for use in several contingencies.[6]

Much can be done by means of permissible suboptimization in such a synthesis to arrive at a best alternative for a given cost. However, it eventually becomes necessary to compare competing alternatives in terms of the ultimate scales of effectiveness. This, then, comprises the final measurement of effectiveness. But because of the great expense in labor the final measurement involves, it should be performed only after as much suboptimization as possible has been performed, and upon as small a set of competing alternatives as possible.

### *Measurement of Effectiveness*

Let us assume that component studies of the preceding kind have been performed for each system of Fig. 4.4, and that the competing alternatives have been synthesized for each contingency. What form, then, does the measurement of effectiveness take? For one thing, each measurement must be made inside a single contingency. It is necessary later to compare measurements across contingencies, but it is not consistent with the real world to vary contingencies (for example, from subsystem to subsystem) during a given measurement.

The measurement model will depend strongly upon the contingency under consideration. This can be illustrated by an example. Consider a contingency in which the enemy strategy is all-out, uncontrolled aerospace attack upon the United States.

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[6] Two specific applications of sensitivity analysis are illustrated in detail in Chapters 8 and 9.

In such a case, much can be learned by assuming that both sides follow essentially predetermined strategies that call for the maximum rate of weapons use, in order to minimize the damage the enemy will inflict. The model then becomes basically a mechanism for tracing out in time the delivery of the various weapons from each side, and then converting this history into final estimates of U.S. and enemy population casualties, and surviving manufacturing capacity and agricultural acreage. The time history will depend upon the flight characteristics and deployment of the weapons of both sides; the final damage to both sides will depend upon whether or not a given weapon survives to launch, whether or not it penetrates to target, whether or not its target is still there upon its arrival, and whether or not it is capable of destroying its target.

While the general nature of this model seems rather clear, many decisions are still unspecified by our assumptions and call for analysis of various subcases. For example, how will the enemy divide his weapons between U.S. military and non-military targets, between bomber targets and missile targets, and so forth?

In this extreme example of a central war contingency, the only random variation permitted within the measurement of effectiveness is the operational kind. Since the performance of weapons is governed by probabilities, any integrated use of weapons, as in a conflict, must also be governed by probabilities. But since any conflict can occur only once, what possible meaning can probabilities have? Any future conflict, although starting in a specified contingency, can actually unfold in many ways and have many final results. In each such unfolding – which might be called a "play" – the component probabilities influence the results. We thus are led to the notion of a *probabilistic model*, the output of which is a probability distribution of effectiveness. Figure 4.6 shows illustrative distributions of effectiveness for two different strategic alternatives (systems) within the same contingency; the horizontal axis gives effectiveness, and the vertical axis gives the percentage of plays in which the effectiveness equals a specific value. For example, alternative 1 should achieve an effectiveness of about one-half in 40 per cent of a large number of plays.

How does one decide within a fixed contingency between two alternatives when their effectiveness is given by probability distributions?[7] Let us assume that alternatives 1 and 2 are of equal cost. As we saw earlier, the criterion might then be to select the alternative with maximum effectiveness. But which of the present two alternatives should we choose? Alternative 1 certainly achieves a high effectiveness, but only some of the time. In order to make a decision, we must specify some preference for different kinds of probability distributions.

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[7] This question will be taken up at greater length by Albert Madansky in Chapter 5.

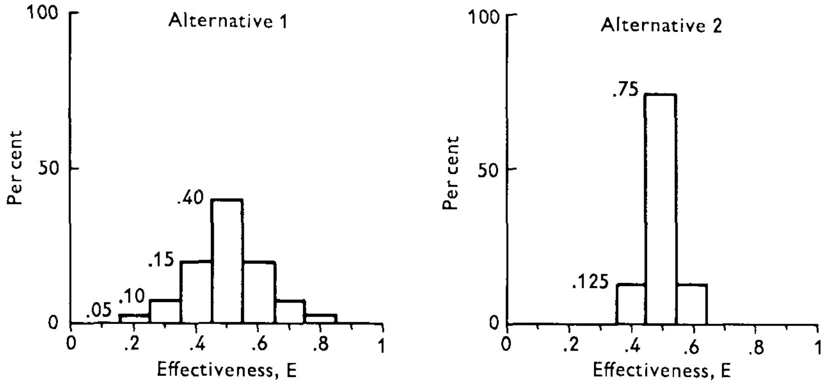

Fig. 4.6 – Percentage of plays with effectiveness, E

Often for reasons of convenience rather than accuracy, a common choice is to prefer the distribution that has the largest average value, because the model that gives such outputs is usually easier to build than one whose output is probabilistic. Clearly, even the average value tells us a good deal about the performance of alternative 2. Were we, therefore, to use average values, our criterion would then be to select the alternative with the largest average value of effectiveness. In the case shown here, such an average-value criterion does not determine a choice, since both alternatives have the same average effectiveness: one-half. However, even though an average value criterion cannot distinguish between alternatives 1 and 2, many a decisionmaker can. For example, if other inputs suggest that an effectiveness of seven-tenths is the minimum useful outcome, then alternative 1 could be the preferred choice.

With a large number of cases to be considered, it is often impossible to carry along distribution functions such as these, let alone expect the decisionmaker to digest them all. A common technique for reducing the distribution to a single number is to employ a criterion such as this: for fixed cost, select that alternative which maximizes the probability that a given effectiveness, such as seven-tenths, is exceeded. In the case at hand, we would choose alternative 1, which has a probability of about 10 per cent of exceeding a seven-tenths effectiveness.

The results of measuring the effectiveness of alternatives for a single contingency and fixed cost might then take the form shown in Fig. 4.7. Numbers to the left of the virgule express the average effectiveness; those to the right, the probability of exceeding a given effectiveness, such as seven-tenths. Both numbers are given for each alternative on each of the various scales, A, B, C, D, E, which might be the fraction of enemy population surviving, United States population surviving, and so forth.

Contingency k

| Alternatives | EFFECTIVENESS SCALES | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| I | .4/.1 | .6/.4 | ~ | ~ | ~ |
| II | .5/.05 | ~ | ~ | ~ | ~ |
| III | .3/0 | ~ | ~ | ~ | ~ |
| IV | .7/.5 | ~ | ~ | ~ | ~ |

Entry code:
Average effectiveness
.4/.1
Probability of achieving at least .7 effectiveness

(Fixed cost C)

Fig. 4.7 – Fixed contingency effectiveness results

When the table is completely filled in, we thus have an array of effectiveness numbers for each important contingency.

Although this kind of summary information can be useful at various decision levels, it is worth noting that it measures the effectiveness of each alternative at just one point in time – say, that corresponding to the end of a war. A decisionmaker will usually be interested in having additional information: How might the conflict progress? What decisions must be made during its course? How can it be terminated (and at what time and cost)? Analysis usually generates data relevant to these questions, although they are suppressed in Fig. 4.7.[8]

*Criteria*

Criteria are needed to select preferred alternatives within fixed contingencies. The principal problem arises from the need for multiple effectiveness scales. For example, for the specific contingency described earlier, in which the enemy strikes U.S. cities and military targets first and we respond in

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[8] For example, the time history of delivery of weapons can be of use in both policy and design questions, such as what decision rate must be supported in the national command center, what data inputs are important there, and so forth. Similarly, a history of the variation of an effectiveness measure during a conflict can also provide insight into the problems of war prosecution and termination, even for an all-out war of the type we are discussing, where the strategy is predetermined.

an all-out attempt to limit U.S. damage, we might have the results shown in Fig. 4.8. How may a selection be based upon such results? We could decide immediately if there existed a situation of essential dominance; such dominance, however, occurs rarely. We could try to combine the three U.S. scales into a single scale, such as the expected level of subsistence of the United States ten years after the war, and then do the same for the enemy scales. This would require considerable but worthwhile research, similar to that we noted before as being necessary in making use of suboptimizations. But while some means are available in theory for making such a combination, today it is not possible.

| Alternative | Enemy Surviving (%) | | | U.S. Surviving (%) | | |
|---|---|---|---|---|---|---|
| | Population | MVA | Agriculture | Population | MVA | Agriculture |
| I | 60 | 50 | 75 | 70 | 50 | 50 |
| II | 50 | ~ | ~ | ~ | ~ | ~ |
| III | ~ | ~ | ~ | ~ | ~ | ~ |
| IV | ~ | ~ | ~ | ~ | ~ | ~ |

Fig. 4.8 – Typical fixed contingency results (fixed cost)

The U.S. and enemy scales cannot be combined into a single scale as meaningful as post-war subsistence level. In general, therefore, judgment must be used to balance enemy damage and U.S. damage. If a decision cannot be made within a contingency, then the analyst simply must carry along several alternatives to the cross-contingency level of decision.

Criteria for use across contingencies will, in general, be more complicated, except when one alternative is dominant within and across all contingencies. Since such dominance is most uncommon, many contingencies must be considered. For example, an analysis to determine the proper allocation of a budget between offense and defense would certainly have to take account of most of the following major contingencies: all-out uncontrolled nuclear exchange initiated without warning by either the United States or the major enemy; such exchanges initiated out of a crisis; controlled exchanges of the preceding kind; accidental initiation; and, finally, various levels of conflict involving n<sup>th</sup> countries and the United States. Needless to say, the large number of contingencies possible provides a strong motivation to develop techniques for eliminating some of them. Three in particular – "best estimate" analysis, "worst case" analysis, and "*a fortiori*" analysis – are widely used.

A "best estimate" analysis is one in which the uncertain factors describing a contingency are assumed to coincide with the analyst's best estimates thereof. This will sometimes be a valid technique; in most cases it will not, unless accompanied by appropriate sensitivity analysis.

A "worst case" analysis is one in which the factors used to describe the enemy are selected to make him exceptionally effective, intelligent, and aggressive. The philosophy is that an alternative which is effective in this worst contingency will probably be effective in all reasonable ones. Its shortcoming is that alternatives designed to be effective in worst cases tend to be either inadequate or prohibitively expensive, and thus are seldom procured. All alternatives then tend to get tested against this worst case attack, with the result that no alternatives get procured, even though other reasonable contingencies can be met by them. For example, our inability to handle an all-out attack by a highly aggressive and sophisticated enemy has delayed development of ABM systems able to handle less difficult contingencies, such as accidental or n<sup>th</sup>-country attack. On the other hand, it is appropriate to use a worst case as the basis for designing a deterrent, for obvious reasons.

But even if a "best estimate" or "worst case" analysis points clearly to a preferred alternative, other contingencies should be examined, in order to understand the alternative's usefulness under what are possibly more likely contingencies. For example, the possibility that a given ABM alternative will effectively defend against most n<sup>th</sup>-country attacks, as well as many accidental attacks by our major enemy, is important knowledge which should be reflected in deciding whether or not to buy ABM, and in evaluating its selection and design.

It is sometimes possible to exclude an alternative by using a device just the opposite of the "worst case" approach. The alternative under consideration is designed as optimistically as possible, and the contingency most favorable to that alternative is chosen. Then, if the alternative still performs badly, it can be discarded. Such a technique is called "*a fortiori* analysis."

To avoid using any of these three techniques to discard important contingencies inappropriately, the analyst should increase the level of aggregation of the final synthesis. This process, which reduces detail and broadens the spectrum of contingencies which can be handled, can legitimately be carried to the point of expanding the scope of the analysis to include national constraints which limit the number and quality of programs a nation can undertake. Thus, if the total defense budget of a major enemy has historically been allocated according to some traditional pattern, this pattern should be considered in estimating the enemy's budget levels for offense and defense, achieved levels of technology in many disparate fields, and so forth.

But it is no less true at the end of a study than it was at the beginning that systems analysis always involves human judgment. There is, of course, a natural desire to attach probabilities to contingencies, so that those of low probability can be ignored, or the results of analyses within several contingencies can be weighted and combined into a single measurement of effectiveness. It is also true that attempts to attach either absolute or relative probabilities to contingencies will in most cases fail, so that no such combination can take place. Therefore, the ultimate conclusions will have to be made by the subjective consideration of the important contingencies, taken individually and severally. The need for professional military, political, social, and scientific judgment in the ultimate decision process is thus clear.

In general, it is not desirable (or possible) to specify detailed criteria before the results of a study are in hand. Rather, the results should be used to determine what goals are in fact attainable, which contingencies it is feasible to meet, where large payoffs for small investment may occur, and so forth. Politics has been called "the art of the possible." So is military strategy and its support by military systems: We can readily identify *desirable* goals, but usually we can specify *attainable* goals only *after* research. Thus, criteria should not precede results, but should follow, and goals should not be static, but should change to conform to the realities of engineering, science, military operations, and politics.

### SUMMARY

This Chapter can be summarized very briefly. A principal aim of systems analysis is to find the relationship between cost and effectiveness, such as is illustrated in Fig. 4.9.

The uncertain nature of many aspects of the world forces the analyst to consider different contingencies, within each of which this relationship between cost and effectiveness must be estimated. Therefore, in many problems there are really *two* fundamental variables – cost and contingency – upon which the effectiveness of an alternative depends. This can be signified by a three-dimensional, rather than two-dimensional plot, as in Fig. 4.10.

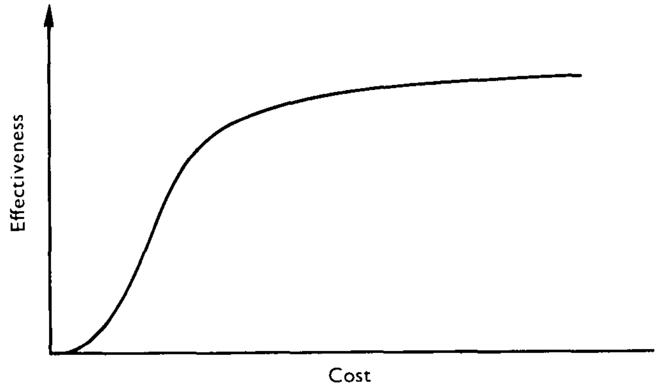

Fig. 4.9 – Cost and effectiveness

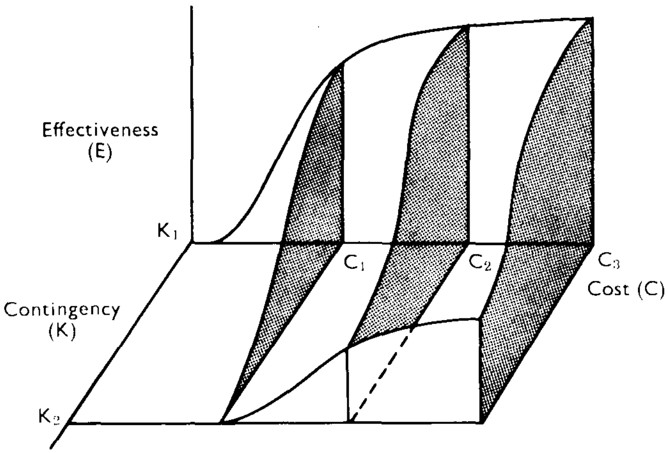

Fig. 4.10 – Cost, effectiveness, and contingency

Clearly, as the contingency and cost are varied, the effectiveness traces out a three-dimensional surface, giving effectiveness versus both cost and contingency. This surface can be sketched out by selecting several contingencies, such as $K_1$ and $K_2$, and estimating, within each, the effectiveness-cost relationship, as illustrated in Fig. 4.10. At the same time, the relationship between contingency and effectiveness for several fixed costs ($C_1$, $C_2$, and $C_3$) can be indicated.

The principal problems of systems analysis derive from the fact that the effectiveness scale is really many scales, and from the need to consider alternatives across contingencies. Because of the difficulties it introduces, analysts and decisionmakers tend to ignore this third dimension of the problem, often by restricting the analysis and decision to that contingency which fits their own preconceptions or biases. Since, essentially, the contingency analyzed determines the outcome of the analysis, this arbitrary restriction leads to decisions that support the bias of the analyst or decisionmaker, rather than objective results. This is a major source of error in the use of analysis today. Of course, to these difficulties must be added the need to synthesize already broad component studies into even broader studies, with the attendant need to combine performance estimates for dissimilar systems about which our knowledge is not uniform.

These problems are difficult, and it is clear that judgment still must play a large part in final decisions. But systems analysis can do a great deal toward placing that judgment on a firm, objective basis.