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MEMORANDUM

RM-3452-PR

JANUARY 1963

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MILITARY SYSTEMS ANALYSIS

E. S. Quade

PREPARED FOR:

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PREFACE

This Memorandum surveys systems analysis as applied to military problems.

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SUMMARY

Systems analysis is an approach to complex problems of choice under uncertainty by systematically examining the costs, effectiveness, and risks of the various alternatives. This Memorandum attempts to survey the problems and procedures of such analysis when applied in a military context.

MILITARY SYSTEMS ANALYSIS

The analysis of weapons and strategies for future wars presents a new kind of problem, different in a practical sense from any treated by operations analysts in World War II, or even in the Korean War. The aim in planning may now be how to deter war or even how to disarm with security, as well as how to wage war. A broad context, a rapid rate of technological change, and a resourceful enemy clothed in secrecy make extremely hazardous any prediction of the environment—usually five, ten, or more years in the future—in which the weapons and strategies are to be used, and the effect of their introduction into that environment. In this area of long-range military planning, as opposed to the operational use of given military units or weapons, piecemeal component optimizations and cost-effectiveness comparisons of competing postures and strategies must be replaced by an over-all treatment in which emphasis is placed on an integrated simultaneous consideration of all the major relevant factors.

Systems analysis, that is, analysis to suggest a course of action by systematically examining the costs, effectiveness and risks of alternative policies or strategies—and designing additional ones if those examined are found wanting—represents an approach to, or way of looking at, complex problems of choice under uncertainty. It was developed originally to deal with long-range military problems but is now used extensively by managers and engineers of large industrial enterprises, such as telephone companies and producers and distributors of electric power. It offers a means of discovering how to design or to make effective use of a technologically complex structure in which the different components may have apparently conflicting objectives; that is, an approach to finding the best balance

among risks, objectives, and cost. Its purpose is to place each element in its proper context so that in the end the system as a whole may attain its objectives with a minimal expenditure of resources.

It was not the systematic approach but the subject matter which originally suggested the name. The first post-World War II military studies were primarily concerned with weapon systems. Evaluations undertaken to enable a decision maker to choose among systems, to discover whether a given system could accomplish the desired objectives, or to set up a framework within which tests of the system could be prepared were naturally called "systems analysis." With slightly different emphasis, the terms "systems research," "systems design," "systems engineering," and, lately, "operations research"* are also used.

As an example of a relatively narrow problem in which a systems approach might be helpful, let us examine one which might arise in choosing a next-generation air defense missile from among several possible configurations. Consider, for example, guidance and control. Without taking a "system" point of view, it might seem obvious that if the accuracy of our missile can be improved, the result will be more enemy missiles or planes shot down. It does not follow at

* There is no clear line of demarcation between operations research and what we are calling systems analysis; the difference is a matter of degree. Until recently operations research has tended to emphasize mathematical models and optimization techniques. The operations-research analyst 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. The systems analyst, on the other hand, is likely to be forced to deal with problems in which the difficulty lies in deciding what ought to be done, not simply in how to do it. In such a situation, far more attention must be devoted to establishing objectives, criteria, and alternatives. The total analysis is thus a more complex and less neat and tidy procedure which is seldom suitable for a quantitative optimization over the whole problem.

all, however, that the missile with the highest accuracy will necessarily maximize the effectiveness of the over-all defense system or, for that matter, will even give the missile component of the system its highest potential for killing enemy vehicles. Any numerical values which measure the kill capability of a missile-defense system must depend on at least four factors: first, the number of missile emplacements within whose range the invaders must fly; second, the number of missiles that can be launched during the time the enemy is within range; third, the probability that a given missile will be operative; and fourth, the probability that an operative missile kills its target. An increase in the accuracy of the missile would probably increase this fourth factor. But this would result in an over-all increase of kills only if the values of the other factors were not materially lowered by whatever change was necessary to bring about the increase in accuracy.

If, for example, additional guidance and control equipment were added to the missile to improve its accuracy, the resulting increase in weight might reduce the range or the speed of the missile. This in turn could reduce the number of missiles that might be launched in an engagement. Also, the greater complexity of more accurate guidance equipment might degrade the reliability. Consequently, in spite of the increased accuracy, the over-all effectiveness might be reduced. Moreover, there is the very likely possibility that the more accurate missile might cost more and, since the total expenditure is certainly a constraint, the purchase of missiles which are individually more accurate might lead to fewer launching sites and fewer missiles.

Indeed, in these days of deterrent weapons, certain less obvious factors—for example, the state of readiness, the vulnerability, and the susceptibility to countermeasures—may contribute equally to deterrence and be the items

which dominate the costs of the system. The certainty with which a weapon can be fired after an attack may be more essential than its accuracy. Operational and logistic factors such as mobility, data requirements, communications, supplies, maintenance, personnel, and training must all be considered in a systems approach. For example, before deciding to use an unusual substance as a fuel, on the grounds that it would enhance the range of the missile, the logistical implications in the decision must be investigated. The fuel may be so toxic that it will require inordinately complex handling for supply, transport, and storage. If so, the over-all performance of the system may be degraded, or the costs raised, in spite of any increased range or speed that might develop.

Thus, in this problem of choosing an air-defense missile, a systems approach is indicated. The context must be broad enough to embrace everything pertinent to all the alternative systems. The analysis would ordinarily take one or the other of two equivalent forms. For a given desired level of military effectiveness, the systems analyst might attempt to determine which alternative, or combination of alternatives, will imply the least cost. Or, for a specified budget level, he might try to find out which alternative, or combination of alternatives, will maximize effectiveness. In either case, the total systems analysis would require numerous substudies—for example, operations research to investigate problems of deployment or logistics, cost analysis to estimate the dollar costs of the several alternatives, and possibly even war gaming to suggest enemy penetration tactics.

The simplest category of systems analysis involves a choice from within a class of essentially similar alternatives. The problem of choosing the next-generation air-defense missile belongs to this category. The possible alternative missile systems may differ widely with respect

to accuracy, range, payload, and certain other characteristics, such as alert status. But they are likely to be similar in certain fundamental aspects in which the uncertainties are the greatest—for example, in the estimates associated with how far their performance in combat will fall below that of the proving ground, in enemy reactions to their development and use, and in their logistics and support problems. Since they are essentially similar means for accomplishing the same objectives, and are associated with the same time period, many uncertainties are likely to affect all designs in the same direction and approximately to the same extent. In analysis in which the alternatives are relatively similar, it is easier to take uncertainty into account and to apply measures to alleviate its consequences; also, one feels that the failure to handle this factor adequately is not so likely to invalidate the analysis.

On the other hand, a broader problem for systems analysis might involve the design of an entire air-defense system to protect the United States from damage. This would be difficult, but not merely because of the wider context involved. The value of an air-defense system is measured by more than its ability to prevent damage in event of a surprise attack which begins all-out war; for example, in peacetime it polices our borders and prevents intrusions. Better protection, however, results from preventing war, or, if war comes, from keeping it away from our country. Doing this depends on offensive power and national policy for using it—and on air defense. Thus the problem of finding agreement on a working basis for objectives and criteria is not likely to be an easy one.

Even after criteria and objectives have been tentatively set, considerable practical difficulties remain. Here, alternative subsystems with complementary but essentially different tasks, such as radar and antimissile missiles,

would compete for resources. Moreover, even with weapons which have essentially the same objectives, say air-defense missiles for point defense and those designed for area coverage, new difficulties arise because such factors as the warning times required for their employment, their differing utilities under different enemy tactics, and even the support structure may be entirely different. The level of knowledge about the various ingredients will be different. Of course, for weapons such as aircraft there is much past experience to guide the investigator with respect to such things as maintenance requirements, reliability, and the like. For missiles, this backlog of experience does not exist. But even more serious are the effects of uncertainties about alternatives which contribute to damage reduction in entirely different ways—say, shelters and alert missiles. Further, since (as we mentioned earlier) a better way to prevent damage is not to have a war, the analysis has to consider also how these elements affect the likelihood of war, as well as the chances of survival if war comes.

It is not easy to tell someone how to carry out systems analysis. We lack adequate theory to guide us. The attention of the practitioners, when it has turned to methods, has been focused mainly on the development of mathematical techniques. This attention has met with great success. Models have now become easier to manipulate, even with many more variables represented. Computational obstacles cause comparatively little difficulty. It is the philosophical problems, such as occur in providing assurance that the model is meaningful, in devising schemes to compensate for uncertainty, or in choosing appropriate criteria, that are troublesome. This lack of a guiding theory must be expected, for systems analysis is a relatively new discipline.

Systems analysis, particularly of the type required for military decisions, is still largely a form of art and

not of science. An art can be taught in part, but not by means of definite fixed rules which need only be followed with exactness. Thus, in systems analysis we have to do some things that we think are right but that are not verifiable, that we cannot really justify, and that are never checked in the output of the work. Also, we must accept as inputs many relatively intangible factors derived from human judgment, and we must present answers to be used as a basis for other judgments. Whenever possible, this judgment is supplemented by inductive and numerical reasoning, but it is only judgment nonetheless.

One hope for guidance is to turn to science. The objective of systems analysis and operations research, 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 systems analysis seem to be more nearly engineering than science. For purposes of distinction, one might say that science seeks to find things out while engineering uses the results of science to do things well and cheaply. Systems analysis has this latter objective; while every possible use of science and scientific methods is made, additional guidance is required, for it is necessary to decide what is well and what is cheap in each given situation.

Thus, systems analysis is sometimes described as the application of the "scientific method" to problems of economic choice. Even though it is by no means clear that there is any unique method which can be termed scientific, the analysis advances through something like the following stages:

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| FORMULATION | - clarifying, defining, and limiting the problem; |
| SEARCH | - determining the relevant data; |
| EXPLANATION | - building a model and exploring its consequences; |

INTERPRETATION - deriving the conclusions;
VERIFICATION - testing the conclusions by experiment.

A systems analysis always involves the first four of these stages but frequently omits the last. In military systems analyses, experiment is ordinarily not available; if we are lucky, our weapon system will be obsolete before there is a war, and we will never find out whether it was really satisfactory or not. The analysis, however, advances by iteration, passing through these stages more than once.

The discussion of method is divided into four sections, corresponding to the first four stages listed above.

Formulation

Formulation implies an attempt to isolate the questions involved, to define the meaning of the variables or factors that are operative, and to state relationships among these factors. The relationships may be extremely hypothetical, since empirical knowledge may be in short supply, but they will help to make the logical structure of the analysis clear. In a sense, this is the most important stage, for the time spent restating the problem in different ways, redefining it, or expressing its limits, brings to light whether it is spurious or trivial and points the way to its solution. The tendency all too frequently is to accept the original statement of what is wanted exactly as proposed, and then to set about building a model and gathering information, scarcely giving a thought to how the answer will contribute to the decisions which it is trying 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 the customer's view of what the problem is.

An analogy with medical practice may be drawn. No doctor ignores a patient's description of his symptoms, but he cannot allow the patient's self-diagnosis to override his own professional judgment. The medical analogy is not entirely applicable, however—the businessman or military commander ordinarily knows more than anyone else about his operations and what, if anything, might be wrong with them. Even so, he may not be so sound in his knowledge of how these operations affect, and affected by the context in which they occur.

How is the analyst to know his formulation of the problem is superior? His one advantage lies in analysis. That is, the process of problem formulation itself should be the subject of analysis. The systems analyst always has some idea as to the possible solutions of the problem; otherwise, he probably should not be working on it, for his analysis will prove to be too formal and abstract. At this early stage the analyst essentially makes an attempt to solve the problem before the facts are known. It is this attempt which gives him a basis for better formulation.

The problem itself does not remain static. Interplay between a growing understanding of the problem and of possible developments will redefine the problem itself. Primarily, as the result of discussion, the original effort to state the problem should suggest one or more possible solutions or hypotheses. As the study progresses, these original ideas are enriched and elaborated upon. Each hypothesis serves as a guide to later results—it tells us what we are looking for while we are looking. The final statement of the conclusions and recommendations usually rests on a knowledge of facts about the problem which are not known to the analyst at the start. Frequently, a hypothesis must be abandoned and an entirely new one considered.

Analysis must be an iterative procedure; that is, a process of successive approximation. The various stages in analysis—problem formulation, data collection, model building, and computation—may follow each other in that order only within a single iteration; the tentative solution we obtain at the end of the first approximation helps us to better prepare a second formulation of the problem. Figure 1 attempts to indicate this iterative character of analysis. In a certain sense it is impossible to formulate a problem completely before it is solved, or, in other words, the final problem statement may have to be written simultaneously with the final answer. It is not a mistake to hold an idea in the early stages as to the solution; the pitfall is to refuse to abandon such an idea in the face of mounting evidence.

Even for small-scale individual problems, the number and complexity 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 anything like the complete range of possible alternative solutions may be impossible. The vast majority of alternatives will be obviously inferior; there is no harm in leaving these out. The danger is that some solution which is better than that uncovered by the analysis will also have been left out. The number of alternatives available in completely unrestrained situations are too numerous to be examined. Constraints must be imposed, but by preliminary analysis, not arbitrary fiat. Such constraints must be regarded as flexible so that they may be weakened or removed if it appears in later approximations that their presence is a controlling factor.

Something must always be left out, otherwise problems are too big. For example, the decision to use a particular air-speed indicator in a new fighter should fundamentally rest on the military worth of the available indicators. It

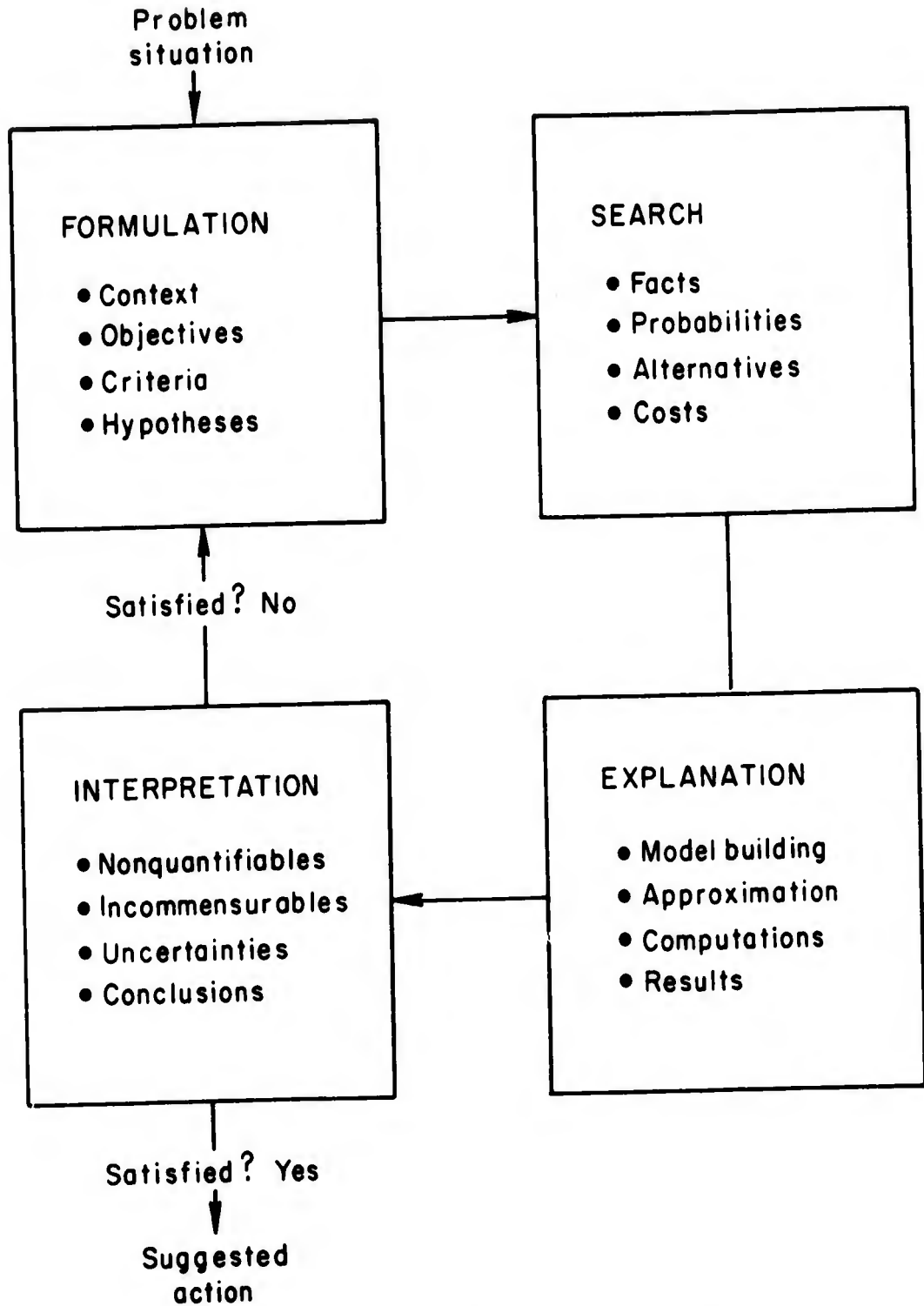


Fig. 1 — Activities in analysis

is futile to try to make this choice by considering all possible wars in which this equipment might be used. Yet, even though it may be beyond his capability to do a complete job, the analyst can at least do some thinking about the larger problem. The dangerous path is to reduce the problem by fixing factors which would have been allowed to vary, if sufficient thought had been given to the larger problem.

Certain elements are common to systems analysis as well as to every problem of economic choice, although they may not always be explicitly identified:

1. The objective (or objectives). Systems analysis is undertaken primarily to suggest or recommend a course of action. This action has an aim or objective. Policies or strategies, forces or equipment are examined and compared on the basis of how well and cheaply they can accomplish this aim or objective.
2. The alternatives. The alternatives are the means by which objectives can be attained. They need not be obvious substitutes or perform the same specific function.*
3. The costs. Each alternative means of accomplishing the objectives involves certain dollar costs or specific resources used up.
4. A model (or models). This is a set of relationships, mathematical or logical, relevant to the problem at hand, by means of which the costs incurred and the extent to which the objectives are attained are associated with each alternative.
5. A criterion. This is the rule or test needed to tell how to choose one alternative in preference to

* Thus, to protect civilians from air attack, warning shelters, "shooting" defense, counterforce, and retaliatory striking power are all alternatives.

another. For each alternative, it attempts to measure the extent to which the objectives are attained as compared with the costs or resources used up.

A characteristic of systems analysis is that the 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 wrong objective means that the wrong problem is being solved. The choice of the wrong alternative may merely mean that something less than the "best" system is being chosen. Frequently we must be satisfied with merely a demonstration that a suggested action is "in the right direction," anyway. This may be all that is possible.

In the choice of objectives, the iterative character of systems analysis stands out. It is impossible to select satisfactory objectives without some idea of the difficulty and cost of attaining them. Such information can only come as part of the analysis itself.

The problems in the selection of suitable objectives and criteria are the most difficult in systems analysis. References [2], [3], and [4] contain detailed discussion.

The costs to be considered in choosing among alternatives, moreover, should be the "new" costs, that is, the net additional resource drain or "incremental cost" that would be incurred because of the choice of a particular alternative. Because a certain system may inherit facilities, personnel, or equipment from previous systems, its incremental costs may be much lower than what it would cost if it were to exist "in isolation." Also in comparing military capabilities, costs have sometimes been computed on the basis of what the various systems would cost independent of the existence of other systems or other

capabilities. In this light consider, for example, a Navy supercarrier. In a paper comparison to estimate its value in a limited-war role, if no credit were assigned to its central war capabilities, then on a cost-effectiveness basis it would be handicapped unfairly in comparison with a weapon system that had only a single role.

Great attention must be paid to initial conditions; that is, to the assumptions which limit the problem and set the background against which the initial attempt at a solution is to be made. The situation is not like that of an empirical science, which starts with observed facts, but more like that of mathematics, where the results take any "validity" they might have in the real world from the initial assumptions. The difference is that for the systems analysis to give correct guidance, it is important that the assumptions be the "right" assumptions.

Once the problem has been broken down into its components—which is what analyzing the problem means—some of the components can be further analyzed, using various techniques; but others may defy analytic techniques. In that case, because the problem has been broken into smaller pieces, the systems analyst may be able to find individuals who have direct, sound experience and on whose "considered" judgment he can rely.

Considered judgment differs from intuitive judgment in that the logic behind the opinion is made explicit. Both are based on an individual's experience and background, but when the reasoning is explicit, an observer can form his own opinion from the information presented. Judgment permeates systems analysis—judgments as to which hypothesis is better than another, or which approach is more fruitful, or what facts are relevant. The ideal is to keep all judgments in plain view.

Uncertainty in long-range military planning problems being as great as it is, it is well—particularly early in

the study—not to attach much significance to small differences in cost and effectiveness of alternative systems. Specifically, it is important to look for differences of the sort that have a chance of surviving any likely resolution of the uncertainties. The question to address is which alternatives have a clear advantage rather than the question as to precisely how much better one alternative is than another or even, initially, which ones move us toward the attainment of the objectives.

Search

This phase is concerned with finding the facts, or evidence, on which the analysis is based. It is necessary to look for ideas (and evidence to support them), including the invention of new alternatives, as well as to look for facts. Unless we have alternatives, and ideas about them, there is nothing to analyze or to choose between. If in the end we are to designate a preferred course of action, we must have discovered earlier that such a course exists. In long-range problems, the total number of alternatives may be endless, and we must use judgment to eliminate the unreasonable.

Many facts are hard to come by. The actual operational performance of future weapons in combat cannot be predicted with any degree of certainty. Purely theoretical studies or operations research of weapon characteristics must be depended upon. In systems analysis as contrasted with most other forms of engineering, a great many more inputs are a matter of judgment rather than a result of measurement or engineering analysis.

When should an inquiry stop? It is important to remember that in this sort of a problem, inquiry is rarely exhaustive. Inquiries are partial, and the decision-maker must get along without the full advantage of all the potentiality of operations research and the scientific

approach. Inquiries cost money and time; they cost in whatever values one is dealing in. They can cost lives; they can cost national security. It might be interesting to know what the Russians could do if we succeed in dropping an armed Atlas on Moscow. It might be an easy observation to make, but some of the costs seem to prohibit this type of investigation. One should never fall into the error of feeling that inquiry is free of cost. There are many contexts in which we can ignore the cost of inquiry; but paradoxes arise if we allow ourselves to forget that almost all inquiries must stop far, far short of completeness, either for lack of funds, of of time, or of justification for spending further funds or time on them. It is out of the question to collect all the information that is required for exhaustive analysis, and it is out of the question to process it.

As an analogy, consider the example of a physician who uses a clinical laboratory to help him decide whether or not his patient has one of several obscure ailments which have many similar symptoms. Even when all the reports are in, the doctor's inquiry may not be complete. He could probably do a lot more laboratory analysis. If the problem is simply one of diagnosis, one of the very best procedures would be to slaughter the patient and perform a thorough autopsy. The cost here is prohibitive, not only prohibitive by the standards of modern society but prohibitive simply by the fact that the physician's goal is to help the patient live a longer and fuller life. He would only frustrate himself if he bought knowledge at the price of the life he is trying to guard.*

* This is not to say he might not risk life in trying to guard it; he might order such tests as a spinal puncture or a liver puncture, or other inherently dangerous procedures. Many diagnostic procedures are dangerous and are used when the danger is justified, but a doctor will not make a complete sacrifice of what he is trying to protect.

Explanation

After obtaining some idea of what the facts and alternatives are, it is necessary to build up some way to explain them and to determine their implications.

In order to make much progress with real-world problems, we must ignore a great many of the actual features of a question under study and abstract from the real situation certain aspects, hopefully, the relevant ones, which together make up an idealized version of the real situation. This idealization we call a "model."

In the general process of formulating a problem and gathering data about it, the analyst will have developed some ideas of what the major influencing factors are, that is, the factors which provide discrimination with respect to the possible courses of action. To produce quantitative results, it is necessary to assign a scale of measurement to each factor and to show its dependence on certain parameters. Next, the interaction of the factors must be described. Then we have a model. That is, the result of isolating those factors pertinent to the problem or the decision at hand, abstracting them, assigning a scale of measurement, and then describing their interactions builds the model.

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. There are thus no "universal" models—that is say, no one model that can handle all questions about a given activity.

Sometimes representation by the model is mathematical, by means of a series of equations or a computer program. At other times, particularly where detailed specification of the relationships between factors in extremely difficult—for example, in studying the behavior of human organization—the representation may be by a simulation or by a war game.

A gaming model cannot be expected to tell us what an optimal response to an uncertain state of affairs might be, but it can do much to make the players aware of such uncertainties and of the necessity of formulating their plans in such a way as to cope with all foreseeable contingencies. Indeed, an important asset to all systems analysis is the spirit of gaming. This consists in explicitly looking at possible moves and countermoves, in examining and designing a wide range of alternatives, and in looking for substitution possibilities—all against a hostile opponent.

It should be emphasized that, in many important systems analyses, no need arises to build formal models explicitly. When such cases occur, the analysis may be extraordinarily effective since it may be completely understood by the policy maker. The essence of systems analysis is not mathematical techniques or procedures. A computing machine or a technique like linear programming may or may not be useful, depending on the problem and the extent of our information. The essential thing is a listing of the alternatives and an examination of their implications and costs in order that they may be compared.

The widely useful operations—research techniques for optimization, when they are used at all in systems analysis, are used much more extensively in component studies than they are at the heart of the over—all problem. Before any mathematical technique can be applied to a real-world problem, we must construct a quantitative model of the processes involved. This model expresses the effectiveness of the alternatives under examination as a function of a set of variables some of which are under control. Once this is done, a solution can be determined mathematically, since formal statements of relationships between the variables exist. The solution obtained from such a model

will be a usable solution to the real-world problem if and only if the model is a reasonably accurate representation of the real-world situation with respect to the question at issue. In situations of great complexity, such as those associated with major military decisions, only pieces of the problem can be represented with confidence. The sub-models for these pieces or components can frequently be put in a form in which they can be handled by techniques like dynamic programming or queueing theory. But even here, the new and more advanced techniques, while they are useful and promise to become more so, are seldom necessary since—except in relatively few instances—more elementary tools are usually adequate.

The design of models to assist in the decision process is in large measure an art, for it requires selection or composition, plus instinct and a sense of form, to achieve a desired effect. Wide experience and the collaboration of many people are helpful; but in cases in which we are modeling a complex future situation, modeling must be accepted as an art.

All of the assumptions of the model must be made explicit. If they are not, this is a defect. A mark of a good systems analyst (or any wise person communicating with others) is that he state the basis on which he operates. This does not imply necessarily that he makes better assumptions but only that his errors will be more evident.

The contrast between the relative amount of time usually spent on designing a model and that spent in computing its consequences can give bias in judging what is important. It is the design of the model and the faithfulness with which it represents those aspects of the phenomena being modeled which are significant for the question under consideration, not how far or how extensively we push the computation.

The validity of conceptual or mathematical models cannot, in the type of analysis we have been talking about, be tested by the methods of controlled experiment. The best that can be done is to test them by their workability. For example, we try to determine answers to the following questions:

- (1) Can the model describe correctly and clearly known facts and situations?
- (2) When the principal parameters involved are varied, do the results remain consistent and plausible?
- (3) Can it handle special cases in which we have some indication as to what the outcome should be?
- (4) Can it assign causes to known effects?

Whether or not one model is better than another does not depend on its complexity, realism, or computability, but solely on whether it gives better predictions.

"Working" the model, trying out various strategies and concepts of operation, is the nearest thing systems analysis has to scientific experimentation. Deductions based on operating the model frequently suggest new directions of effort. That is to say, starting with the relatively few parameters which characterize the systems in terms of the model, it is important first to show what changes in these would improve the performance of a system as measured by the model, and then to consider whether corresponding changes could also be made in the real system which would lead to improved performance in the real world. In this way, working the model contributes to system design.

Two aspects of model building are particularly troublesome: quantification and the treatment of uncertainty.

Some variables are difficult to quantify, either because they are not calculable, like the probability

of war, or because no scale of measurement has been set up, like the effect on NATO solidarity of some unilateral United States action. This leads either to their neglect, for they tend to be ignored, or to their entry only through a qualitative modification of a solution achieved through the manipulation of variables which have been quantified. Thus the effect of the quantitative variables is built in, while the nonquantitative ones are subject to forgetfulness and may be easily lost in the welter of qualitative considerations that must be weighed, when the problem of what action to recommend on the basis of the solution from the model arises.

One argument for the omission of a particular variable is that the solution of the problem is virtually insensitive to it. 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. Insensitivity can occur either because a factor is irrelevant or trivial in its quantitative effects or because it has roughly the same effect on all of the alternatives under consideration. The point is that this insensitivity must be discovered. Sometimes logical reconnoitering is sufficient, but usually analysis is required, with arbitrary values assigned to factors 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,* then how are they to be treated? The usual method is to attempt to take them into account through modification of the solution rather than to

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

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 always have some insight into the range of values that a factor might take, we can, even in the worst cases, assign the factors an arbitrary value and observe the effect on the solution. It seems to be an empirical fact that results seldom come out of optimization problems until they are quantitative; consequently, every effort should be made to quantify.

Systems analysis is concerned with problems in which the essence is uncertainty about the future. Such analysis, as well as any other attempt to answer the same questions, must necessarily face this uncertainty squarely, treat it as an important element in the problem, and take it into account in formulating recommendations. The treatment of uncertainty is not merely a difficulty in principle, but is a considerable practical problem.

Statistical uncertainty—that is to say, uncertainties having more or less objective or calculable probability of occurrence—can be handled in the model by Monte Carlo or other methods. Such uncertainties, like those in cost or missile accuracy, can be annoying, but not devastating, like the "real" uncertainties associated with the prediction of what the environment may turn out to be during the lifetime of the systems under consideration.

These latter uncertainties about the future behavior of things that are beyond the practical ability of analysts to predict belong to the class of real uncertainties. Under real uncertainty, we consider events to which individuals may attach subjective probabilities, like the probability of war, but which we cannot calculate. With regard to air defense, for example, real uncertainty involves such questions as, "Will we have warning? If we

get it, will we believe it? What surprises does the enemy have?" For such uncertainties, there is frequently widespread disagreement about the pertinent probabilities and even confusion and vagueness within any one person.

The best way to compensate for uncertainty is to "invent" a better system or policy which provides insurance against the whole range of possible catastrophes; the difficulty is to discover how to do this.

Sensitivity and contingency analyses help us to select or design the alternatives so that their performance will not be sensitive functions of unknown parameters.

In "sensitivity analysis" several levels are used for values of key parameters—not just the expected or most probable values—in an attempt to see how sensitive the results are to variations in these parameters. The hope is to obtain a dominant solution in which the ranking of the preferred alternative is essentially insensitive to reasonable variations in values of the parameters in question. "Contingency analysis" investigates how a system chosen with one assumption about the environment would measure up to the performance of its alternatives, if radical changes in the environment were to occur. Thus, sensitivity analysis might test the alternatives for a wide range of enemy capabilities or for the consequences of having planned for one level of capability when another is experienced. Contingency analysis might test the alternatives under a change in criteria or compare them in an environment in which France, say, had become part of the Communist Bloc.

Since a system analysis is a study which attempts to influence policy, it must make a convincing comparison of the relevant alternatives. It must demonstrate that some course of action A is better than alternative possible courses of action B, C, D.... To do this, the analysis may have to be done in two stages: First, find out what to recommend, and second, make these recommendations convincing.

After we are convinced to our own satisfaction what the preferred system or policy is, how can we show that under any reasonable assumption the system or policy designed or selected by the analyst is indeed to be preferred? One way to do this is to use either an a fortiori or a break-even analysis. To make an analysis a fortiori, we bend over backwards in making the comparisons to "hurt" the system we think is best and "help" the alternative systems. If it then turns out that after we have done this we can still say we prefer the handicapped system, we are in a strengthened position to make recommendations. Sometimes we cannot do this—say, if we concede the exaggerated performance claims for rival systems and the pessimistic estimates about the systems we like. In this case, we might try a break-even analysis: We find what assumptions we have to make about important values in order to make the performance of the two systems come out to be essentially the same. Then we can simply ask people to judge whether these assumptions are optimistic or pessimistic.

Interpretation

After a solution has been obtained from a model, this solution must be interpreted in the light of considerations which may not have been adequately treated by the model, since the model was but a single representation of the real world chosen by the analyst. The solution of a problem which has been simplified and reduced to mathematical form by drastic idealization and aggregation of the real world factors is not necessarily a good solution of the original problem.

In the attempt to interpret the results of analysis, there are special problems associated with military questions. Many factors used in the computations are not and cannot be measured. Sometimes this is because of time limitations;

other times it is because factors such as the enemy defense strength, or degradation in combat of complicated man-machine combinations, are not accessible to measurement but have to be assessed on the basis of experience or pooled judgment. The results of computations must be examined to see if they depend critically upon estimations such as these.

It is important for the man who is to use analysis to distinguish between what the analysis shows and the recommendations for action the analyst makes on the basis of what he thinks the study implies. Frequently, when new minds—management, for example—review the problem, they bring new information. Even though the solution obtained from the model is not changed, recommendations for action based on it may be.

Practices such as that suggested by the following statement can lead to serious error: "If several alternatives have similar cost and effectiveness, and these results are quite sensitive to the values assigned to the input, some other basis for decision must be found." This may amount to saying that if, after honest analysis, it must be concluded that we are fundamentally uncertain which of several alternatives is best, the issue should then be resolved on the basis of some specious side criterion not originally judged adequate to discriminate. On the contrary, the points to stress, if such results are found, is that the decisions must be made on the basis of forthright recognition of the fundamental uncertainty. The implication is that in this case unique optimization results are not to be trusted, and therefore they should not be trusted.

If, in the judgment of the analyst and those who are to use his analysis, the alternative ranked highest is good enough, the process is over; if not, more and better alternatives must be designed or the objectives must be lowered. Analysis is sufficient to reach a policy conclusion

only when the objectives are agreed upon by the policy makers. In defense policy in particular, and in many other as well, objectives are not, in fact, agreed upon. In these cases, the choice, while ostensibly between alternatives, is really between objectives or ends. Hence, nonanalytical methods must be used for a final reconciliation of views. The consequences computed from the model may provide guidance in deciding which objectives to compromise. It is not obvious how to do this, however, and judgment must again be applied.

By definition, no judgment is known to be correct. Because systems analysis ordinarily goes beyond objective analysis, it relies heavily on considered judgment. No matter what may be the hopes of professional analysts, the judgment applied by the decision maker in the last phase of a study limits the influence of the previous analyses. At its best, analysis can embrace only a part of a broad-scope problem, it gets no foothold at all on some objective elements, and before it organizes an understanding of all objective elements it becomes too complex to handle.

Concluding Comments

The past few years have seen marked changes in the application of systems analysis to military problems. In the words of R. D. Specht, RAND analyst:^{*}

Let me put the differences inaccurately but graphically: In our youth we looked more scientific. That is to say, we attached more importance, years ago, to the business of representing that part of the real world with which we were dealing by a single analytical model. With the context chosen, the assumptions determined, the criterion selected, we could turn our attention to the more intriguing questions of how best

^{*}R. D. Specht, "RAND—A Personal View of Its History," Operations Research, Vol. 8, No. 6, November-December, 1960, pp. 836-838.

to apply modern mathematical techniques and high-speed computers to produce a neat solution from which conclusions and recommendations could be drawn.

There are many problems in the world for which this is a sensible, even a recommended approach. There are problems impossible of solution without the use of the most powerful tools of mathematics and of computers. The optimal distribution of weight and thrust between the several stages of a lunar probe, the determination of its initial trajectory—these are well-defined questions and yield to neat and orderly solution. On the other hand, the stability of the thermonuclear balance or the composition of a strategic deterrent force or the character of the next generation of tactical weapons—these are not questions that may be attacked usefully in this manner, although essential fragments of these problems may be solved analytically. A trivial reason for this is that even modern techniques of analysis are not sufficiently powerful to treat these problems without brutal simplification and idealization. The major reason, however, for the inadequacy of simply optimization procedures is the central role that uncertainty plays in this sinful but fascinating world. No longer are we analyzing a problem with a given and definite context and with specific equipment. We may not have clearly defined objectives. Instead, we must try to design—not analyze—a system that will operate satisfactorily, in some sense, under a variety of contingencies that may arise in a future seen only dimly.

We have learned that new tools—high-speed computers, war gaming, game theory, linear and dynamic programming, Monte Carlo, and others—often find important application, that they are often powerful aids to intuition and understanding. Nevertheless, we have learned to be more interested in the real world than in the idealized model we prepare for analysis—more interested in the practical problem that demands solution than in the intellectual and mechanical gadgets we use in the solution.

The analytic method, in contrast to many of its alternatives, provides its answers by processes which are reproducible, accessible to critical examination, and readily modified as new information becomes available. At the very least, systems analysis can supply a means of choosing the numerical quantities related to the weapon system in such a manner that they are logically consistent with each other, with the general objectives of warfare, and with the calculator's expectation of the future. Systems analysis must be tempered with and used alongside experience, judgment, and intuition. It cannot replace these other approaches, but it can help build a framework in which they can operate more efficiently.

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