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TECHNICAL REPORT - SDC-641-2-13

SYSTEMS RESEARCH WITH SPECIAL REFERENCE TO HUMAN ENGINEERING

(Human Engineering Systems Studies)

Dunlap and Associates, Inc.
429 Atlantic Street
Stamford, Connecticut

SDC Human Engineering Project 20-F-2
Contract N8onr-641, T.O. II
Project Designation NR-784-002

2 January 1952

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FOREWORD

For some time, the need for a systematic approach in the determination of requirements for, and the design of, military equipments and combinations of equipments has been recognized. This need exists not only in the area of operational equipments which human beings use or operate in the performance of their prime military duties but also in the field of the devices or aids which are necessary to train personnel to perform effectively in the combat situation. This report describes a method by which this systematic approach may be made.

The fundamental concepts of human engineering and systems research are first presented and discussed. One method for developing a criterion against which any system performance may be judged is then described and, by way of example, applied to concrete situations. The general rules for conducting a systems analysis are enumerated and the essential role of human engineering in systems research is pointed out.

It is hoped that this report will not only result in efforts to improve the rationale and methodology of human engineering research in systems analysis and systems design but also serve as an impetus to the wider application of the systematic approach in equipment design and arrangement problems.

Vincent J. Shanley
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SUMMARY

This report attempts to define "systems research" in terms of the problems to which it is applicable, the techniques it employs and the research staff it requires. Although the basic methods of investigation are not radically new, the scope and precise techniques of systems research have not as yet been crystallized. Therefore, the definitions and discussions in this report represent tentative formulations. It is hoped that others will add to them and modify them so that eventually there is a rational method of systems research. The main ideas presented in this report are summarized below.

A system is defined as any organization intended to produce goods or services, or both, which are considered useful to the owner. The owner of the system may be the whole nation, an industrial company or an individual; the components of the system may be men or machines or a combination of both; the output of the system may be anything, from "national security" to pin cushions.

Application of human engineering principles is essential to the optimization of systems, but before the best results can be obtained two things are necessary: the human engineer must know how much effect the changes he recommends will have on the functioning of the system, and he must determine which parts of the system will derive the maximum benefit (measured in terms of the over-all operation of the system) from his attentions. In short, the human engineer must apply systems research. Systems research consists of two parts: systems analysis and systems design. The first part is comparable to medical diagnosis and leads to statements regarding ways in which the system should be improved. The second part, systems design, represents the application of all possible engineering techniques in order to meet the recommendations derived from the systems analysis.

In order to determine the improvements needed in a system, some measure must be developed which describes how good the system is. The following criterion of "goodness" or merit is proposed:

$$\frac{\text{Value - Cost}}{\text{Investment}}$$

[redacted]

Value is difficult to measure but this does not mean that it must be ignored. If the purpose of a weapons system, say, can be defined, it may be possible to find a statistical-historical relationship between the extent to which the weapon was used and the degree to which its agreed purpose was subserved; this is known as the historical approach. When Value cannot be measured as directly as this, it can often be estimated more or less reliably, or at least its relationship to Output can be put on a sound reasonable basis.

The relationship of Value and Output is seldom linear; it is frequently sigmoid. Examination of the system and its relationship to the super-system which contains it usually provides clues to the exact relationship between Value and Output. Then, occasionally, the Value term may be by-passed by comparing either the Costs of two systems with the same Output, or the Outputs of two systems with the same Cost.

A system which produces a single kind of Output, such as submarines killed or aircraft shot down, is fairly easy to analyze. Many systems, however, produce a number of different kinds of Output. For example, field artillery may kill and wound men, neutralize weapons, destroy various sorts of material, paralyze communications and other things; and some means must be found for combining all the elements of Output into a single criterion. In cases such as this, the constructional approach has often been used. Here, the mission of the system is broken down into a precise series of sub-missions, in which the importance of each sub-mission is stated, and from which a set of required man and equipment characteristics for each sub-mission can be derived. In using this approach, the technique of specifying "the most crucial role" and attempting to maximize it, without reference to any other role, leads to very poor results. An attempt should be made instead to measure or to estimate the importance of each role the system may subserve as well as the importance of each functional part of the system. It is not necessary, however, to measure importance precisely since, in practice, the results obtained with reasonable, intuitive assessments do not differ significantly from the results obtained with very accurate measurements.

The term "Cost," in this report, is used to refer solely to the operating cost of the system. In many cases, it can be simply and directly measured in dollars. However, there are exceptions to this rule, determined by the condition of the economy of the nation containing the system:

1. During depression periods, real Costs may be so low as to be neglibible.

2. Controls and allocations may fix Costs permissible, so that the problem of Cost does not arise.

3. During periods of inflation, the Costs of men and materials rise roughly in proportion to their scarcity.

Thus, the systems analyst is faced, according to conditions, with the choice of considering Cost in dollars, maximizing Value with the men and materials he is allocated, or attempting to consider true Cost in rather less naive terms than the dollar. Many of his problems fall into the first two categories.

Investment is distinguished from Cost by the fact that it is used before the system goes into production. It must, therefore, exist as the product of other systems before our particular system is built. Once spent, it cannot be used again except insofar as the physical items on which it is expended are flexible and non-specific in nature. Investment, like Cost, is affected by the state of the nation's economy. Therefore, frequently the Investment problem resolves into a problem of Value maximization.

From the detailed examples of systems analysis worked out in this report, a few general rules may be derived. The first step is usually to consider the relationship between Output and Value, which always demands consideration of the super-system of which the system forms a part. The rest of the analysis is then carried out in terms of Output, Cost and Investment. The second step is to break down the system into its component sub-systems at the next lower level, and to estimate their individual performances, the extent to which their performances could be improved, and the relationships between their performances and that of the whole system. The performances of the sub-systems may combine either by addition or by multiplication to give the performance of the whole system. If they combine additively, overhitting must be considered.

The analysis up to this point will usually show which of the sub-systems has the greatest room for and possibility of improvement in terms of its effects on the Value and Cost of the whole system. Further analysis should then be confined to this most crucial sub-system,

and should be carried down to a level where a sub-sub-system, of manageable size and complexity, can be identified. This sub-sub-system should then be optimized, using all the branches of the engineering discipline. Its new Output and Cost should then be substituted for the old in the analysis, and the criterion for the whole system then recalculated. If it is still inadequate, or if further major improvements appear, from the analysis, to be possible, the next most crucial subsystem should be studied.

It is believed that the poor design of many systems, from the human engineering point of view, stems from the lack of general knowledge of human engineering, the inappreciation of the limiting influence which the human operator generally has on the performance of even the most powerful and expensive machines, the lack of identifiable general principles in human engineering of broad applicability, and the almost total absence of knowledge of the quantitative relationships between conditions of work and man's output. Research in human engineering should rise progressively from an ad hoc basis to the discovery of general principles, quantitative relationships, and the limits within which they may be applied. Meanwhile, the job of the human engineer, who is frequently given the task of modifying a machine whose design is already practically frozen, would be considerably eased if designers would leave adequate space and adequate power, and would use links allowing flexibility in situation and type of control.

A review of the present status of the field of human engineering indicates that studies are needed in the following areas:

1. Conditions under which machines should replace men.
2. Display of complex data.
3. Transfer of training.
4. Performance of radar operators.
5. Attention.
6. Selection of men of optimum size.
7. Acceptance of errors.
8. Effects of comfort on output and incidence of mistakes.
9. Fundamental studies of power tracking.
10. Rate of assimilation of new data.

CHAPTER I

INTRODUCTION

A. Purpose of Report

This report attempts to define "systems research" in terms of the problems to which it is applicable, the techniques it employs, and the research staff it requires. A criterion for determining the usefulness of a system is presented, and the components of this criterion (namely: value, cost and investment) are discussed in detail. The report also presents problems which illustrate the application of the criterion; and from these examples, general rules for systems analysis are derived. The report ends with a discussion of the advances human engineers must make if they are to contribute to a more efficient, more economical method of systems building. The report is organized as follows:

Chapter I. Introduction

Chapter II. Criterion of Usefulness

Chapter III. Examples of Systems Analysis and Use of the Criterion

Chapter IV. General Rules for Systems Analysis

Chapter V. Human Engineering and Systems Research

There is no intention of putting forward the views and methods suggested in this report as true and fixed. They represent no more than the summation of the authors' experiences to date, and are badly in need of criticism, extension and correction. It is hoped that others will add to them and modify them with the ultimate objective of reducing the wastage of industrial, military and research effort which must and does result from the present haphazard approach to system building.

B. Human Engineering

The application of scientific information and research procedures known as "human engineering" developed with recognition of the fact that the efficiency of a system is always dependent on the efficiency of

the human operators who control it. The human engineer's responsibility is to specify the design features and working conditions which will produce optimal human performance; and he derives his recommendations from available information pertaining to such things as body size, the capabilities and limitations of the sense organs, the optimum conditions of temperature, etc., in the working environment, and the rate at which men can absorb and act upon information.

In the past, equipment has usually been judged with regard to its cost and efficiency as a piece of equipment, not as a functional part of a system. This is in no sense the fault of the engineer: he has been presented with specifications and he has met them. It is the specifications which have most often been inadequate, primarily because they were based on judgment, unaided by measurement and analysis, and on an atomistic viewpoint. Similarly, the technique for improving the design of systems in operation has often been irrational. Essentially, it has consisted of isolating each human or mechanical part and inspecting it with the view of improving its "efficiency." This atomistic approach proves successful if all parts of the system can be perfected and if the production of optimum conditions for one part of the system does not have any adverse effects on the cost or efficiency of other parts. In most cases, however, particularly in time of war when production efforts and raw materials are limited, a choice must be made with regard to which components in the system will be developed and improved. Unless the interrelationships within the entire system are understood, there is a possibility that the money and effort spent on the parts selected for optimization may be wasted because of limitations (bottlenecks) elsewhere in the system. Moreover, a degree of perfection may be achieved which is unnecessary or even undesirable. For example, a high degree of accuracy may be obtained at the expense of speed in a system where the latter is more critical to total effectiveness.

In broader terms, when a country is faced with total warfare, effort spent on one system must perforce be denied to another. This is true not only of industrial effort, or military manpower, but also of the rare skills of scientific research. It is, therefore, essential in producing the country's maximum defense potential to drop the expensive luxury of making all equipment as good as it possibly can be, and instead to make it only as good as its importance and influence on the total war effort demand. In keeping with this objective, the human engineer must understand the interrelationships of all components within an entire

system in order to determine where his efforts should be applied and in order to justify his recommendations. In short, he must apply systems research.

C. Systems Research

A system is defined as any organization intended to produce some sort of goods and/or services which are considered to be useful to the "owner" of the system. A system may consist of an organization of men only, or of men and machines, but nearly all systems consist of organizations of men AND machines. Most systems can be analyzed down into organizations of sub-systems, which have more limited and specialized objectives and outputs, smaller size, and simpler organization.

Systems research includes all those processes of study, analysis, and design which can be applied to systems in order to make them as useful as possible. It may be used, for example, in determining how accurate a radar set should be for a particular purpose, in arranging the equipment in a CIC in the most efficient way possible, in deciding how many antisubmarine vessels the Navy should possess, or in deciding whether two industrial organizations should amalgamate.

Systems research overlaps one segment of the field of operations research, a term coined early in World War II for the application of science to military operations. (Previously, the application of science by the military had been practically confined to the design of military equipment to meet a specification arrived at by processes of judgment rather than scientific evaluation of the needs of the service concerned.) Operations research has grown to cover the whole gamut of military operations from the broad strategic fields studied by such organizations as the Weapons Systems Evaluation Group, through the more tactical problems dealt with by Operations Evaluation Group, Rand, or the Army's Operations Research Office, to the highly specific researches carried out in connection with weapon development--often not formally recognized as operations research. Operations research has usually dealt with collections of systems, and their modes of operating together. It builds up its researches through the tactical to the strategic level. Systems research, on the other hand, has usually been conceived as a narrow segment of operations research since it is concerned with the functioning, in tactical situations, of a single team of men and equipment.

The team of men and equipment has generally been a small and homogeneous one: rarely, an entire ship or aircraft and its crew; more commonly, one part or function of the ship and its crew. A typical example might be a CIC considered as a functional unit of men and equipment, operating in a particular space, and concerned with producing a particular result.

Operations research, moreover, has always--or nearly always--stopped short at the point when a decision can be reached as to the ways in which individual systems--tanks, guns, aircraft and the like--need improvement, often with some suggestions as to how it can be done, but without specifying the detailed engineering means by which the improvement can be made. Systems research does not stop here. It is concerned with building better systems, not using existing ones to the best advantage.

We can, therefore, conceive of systems research as consisting of two parts: 1) analysis (parallel in a sense to medical diagnosis) and 2) the action to be taken as a result of the analysis or diagnosis. Of these, the former is closely akin to the loose body of technique and practice known as operations research, and the latter is an application of engineering methods to any parts of the system shown by stage one to need improvement. Of these engineering methods, human engineering has frequently turned out to be the most fruitful, probably in part because least attention has been paid to human engineering concepts in original design, and because as systems become more complex, their efficiency becomes ever more sharply limited by the powers of the men they contain.

D. Systems Research and Other Applied Research

The methods of systems research do not differ qualitatively from those of other applied sciences. They consist basically of analysis of the system into its components, the measurement of all the things which need measuring and can be measured, assessment (too often at the subconscious informal level) of those things which need measurement but cannot yet be dealt with quantitatively, and the production of synthesized recommendations. Systems research differs from most applied research in the following main ways:

1. The highly complex criteria it employs.

2. The interdependent teams of men and equipment with which it deals.

3. The interdependence of the system being studied and other systems.

4. The very wide variety of technical methods necessary for solutions.

5. The emphasis on probability mathematics and statistical methods.

6. The object of the work: to produce a functional specification or a plan of action, rather than a detailed mechanical drawing, a working model, or an electronic circuit.

7. The fact that the techniques for systems analysis are nowhere taught as a coherent whole, so have to be learned by experience.

The first difference between systems research and most other research--the complex nature of the criteria--is probably the central problem in this type of study, and is dealt with in considerable detail in the next chapter.

The second difference, relating to interdependent teams of men and equipment, is perhaps best covered by careful selection of the research staff. Experience has shown, both in America (systems research organizations at Harvard and at Johns Hopkins) and in England (the various operations research groups in the Service and Supply Departments) that psychologists, biologists, economists, applied mathematicians and statisticians are especially successful at this kind of work. This is to be expected: all are research-minded, all are accustomed to the use of probability methods in complex universes, and all have some grounding in the physical sciences. Basically, what seems to be required is a team of scientists, with a predominantly psychological-biological flavor, but with engineers, mathematicians, and statisticians included for the sake of their special knowledge and viewpoints. This, at any rate, was the official opinion of the British Civil Service Commissioners as a result of wartime experiences in the staffing of operational research organizations.

The remaining differences between systems research and most other applied research are dealt with in the following pages mainly by example rather than by precept, though an attempt is made to deduce general principles which it is hoped will be specific enough to be useful.

CHAPTER II

CRITERIA OF USEFULNESS

Much of the present chapter may appear at first glance to be irrelevant to the job of the systems researcher as at present conceived, and to be the province of those high levels of command which reach policy decisions on broad strategic issues. It may appear even more irrelevant to the human engineer. But, any analysis performed by the systems researcher or by the human engineer must use a realistic, logical criterion if it is to produce sound results. In order to design or redesign systems to have maximum usefulness, some means of measuring or estimating usefulness is absolutely essential. We must be able to tell whether a change we have made or contemplated is a change for the better or for the worse. We need a "criterion" or measure of usefulness. An attempt is made to present a basic criterion in the following pages.

A. Factors To Be Considered

1. Output and Cost in Relation to Value

It seems to be true of all systems, both military and civilian, that their usefulness is increased by their output, and decreased by their cost. In the great bulk of the military systems analysis which has been carried out so far, the cost element has been inadequately considered, if not entirely neglected. If the military has more money than it can use, such an approach is quite satisfactory; but any shortage of funds demands the weighing of several alternative courses of action and choosing that one which gives the most valuable return for the expenditure of the dollars available. In any modern democracy, therefore, cost must be considered; and recent examples of systems and operations research give it considerable emphasis.

Consideration of cost unfortunately brings a major difficulty in its train: attempts merely to maximize output while keeping costs as low as possible no longer always tend to produce the best systems. We can conceive of a case where doubling the output, at a 90 percent increase in cost, would lead to a worse result than leaving the system alone. This would happen if the extra output had a lower value per unit of output. For example, in the industrial situation, the extra output

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might be unsaleable. In the military situation, the extra output might consist of extra hits on a ship already sunk by the original output, or extra accuracy in a reading when the accuracy cannot be used.

Consideration of military systems shows that the value of a system is determined by its output, and nearly always increases when output increases, but that the relationship is seldom a linear one. As an example, take the case of the early warning of enemy air attack which a fleet requires to bring its fighter defenses into action. The output of the early warning system can be regarded as minutes (or miles) of early warning. When the warning is received, the fleet orders aircraft to take off, and vectors them to a position and altitude where they can intercept the enemy. The time required for communications and decisions, the take-off time, and the rate of climb of the aircraft are considerable. Suppose they amount to $\underline{t}$ minutes. Then any early warning output less than $\underline{t}$ minutes will have no effect on the interception of the raid, and consequently will have little value. At the other end of the scale, suppose an early warning time of T minutes allows the fighters to fly out to their maximum range before intercepting. Then an increase of early warning output beyond T minutes will be of less value per minute than increase within the range from $\underline{t}$ to T minutes.

Sometimes increasing output may even reduce value. An example may be drawn from the case of the bomber aircraft. Output may be measured in tons on target per unit time. In the World War II operations against Caen (in Northern France) and Cassino (in Italy), very large tonnages of bombs were dropped on the targets. Analysis of the operations after the event demonstrated that the targets were overbombed to such a degree that the ruins actually impeded Allied operations, both by making our subsequent supply operations more difficult, and by creating strongpoints in the rubble which the enemy used to advantage. Here, less bombs would have been more valuable.

2. Investment

Will a criterion of "value minus cost" be sufficiently realistic as a measure of usefulness? Consider two competitive military systems, both having the same output, and hence the same value, and both having the same cost; but one of them being capable of manufacture in every garage and workshop in the country and the other requiring the

[redacted]

space and assembly line facilities of a new unbuilt Willow Run. Evidently the system which does not require us to build a new Willow Run, thus diverting labor and materials from their present uses, is the better system; and evidently, therefore, our criterion should include the investment which the system demands for its manufacture. More important, perhaps, a criterion consisting simply of "value minus cost" would tend to increase with increasing size of the system, and would lead to the irrational result that all systems should be as big as possible. Therefore, in line with normal economic practice, we shall use as our criterion:

$$\frac{\text{Value} - \text{Cost}}{\text{Investment}}$$

The difficulty inherent in attempting to subtract a Cost in dollars or man-hours from a Value in men killed or things destroyed will be dealt with later in the report.

B. Measurement or Estimation of Value

Consideration will show that the Value of a system cannot be defined or measured within the system under analysis: we have to go outside the system to the "super-system" of which ours forms a part to get at its Value. For example, we cannot measure the Value of an antiaircraft battery in terms of any part of the battery itself, but only in terms of its effects on enemy aircraft; and we can only estimate the Value of its effects onenemy aircraft in terms of their effects on our armed forces and our national economy.

Further thought shows that:

1. The Value of any system is the sum of the Values of all the sub-systems it contains, since each sub-system has Value only in so far as it contributes to the Value of the whole system.

2. As we go up the hierarchy of systems in our analysis, we finally arrive at a level where Value is in practice determined by a "policy decision"; that is, by a decision based on judgment and emotion rather than on a self-contained logical argument about an agreed set of facts and interrelationships. The systems researcher then develops the best method of implementing a policy decision.

3. Though systems interact, and their Output depends on this interaction, we need not consider interacting Values, since we make only one translation from Output to Value at the level of the highest system we are considering; below that level, we deal only with Outputs and Costs.

Value is generally very difficult to measure but, of course, this does not mean that it can be ignored or by-passed. Its direct statistical measurement has been achieved in one set of examples: the Values of various forms of infantry support in World War II. This study is briefly described below. In general, it seems likely that similar methods could be used to estimate the Value of any system on which a considerable body of statistical data exists and which was used to different extents in different campaigns or periods.

1. Historical Approach

If the stated mission of a weapon or weapons system may be defined by reference to what it has been shown to have done in the past, or by a policy decision, or by agreement between experts, it may be possible to find statistical-historical relationships between the extent to which the weapon was used and the degree to which its agreed purpose was subserved. For example, if we have two weapons, both of which "are intended" to support infantry soldiers, we can carry out a partial regression analysis dealing with amount of weapon x, amount of weapon y, and amount of success of the infantry z. Statistical and mensurational difficulties abound, but in several practical cases have been overcome with a fair degree of success.[1] Briefly, the procedure was to relate the amount of support (in tons per month, etc.) to the logarithm of the "cheapness of advance" of the supported infantry, cheapness of advance being defined in terms of rate of advance divided by battle casualties sustained. The method has not so far been applied to retreats or stalemate situations. It suffers from the serious disadvantage that it deals only with the past: how weapons

[1] See classified technical memoranda, prepared by Operations Research Office, Dep't of the Army, Numbers ORO T-52, T-75, T-82, T-89, T-104, and T-105.

and tactics existing in the past were applied to a former enemy, rather than how non-existing weapons and tactics could and should be applied to a present or future enemy. It gives, however, reasonable estimates of the relative Values of different weapons systems in realistic situations, and compares on common ground systems formerly incomparable. A fuller account of the work is given later in the present report, but for details, the reports themselves should be consulted.

When Value cannot be measured, it can often be estimated more or less reliably, or at least its relationship to Output can be put on a sound reasonable basis. This was done in the example of the early warning system mentioned in the previous section, and is discussed in more detail below.

2. Value Related to Output

It is generally safe to assume that as Value is caused by and due to Output, Value of a particular system is fixed if Output is held constant: that is, for each system, there is a unique curve relating Value and Output. If this assumption is made, two systems or two states of the same system, can be compared either by holding Output constant and comparing Cost, or holding Cost constant and comparing Output. Either method allows the analyst to arrange any number of variates of a system in order of usefulness,[1] but neither enables him to say how much better one variate is than another, nor which of two systems is the better unless both have Output of the same nature. If comparisons are made on this basis, they should be done at several levels of Output, so that the resulting graphs of relative Costs for the same Output at each level give an indication of the circumstances within which the comparison is valid.

Moreover, in dealing with Output, it is important to realize that the Output of a system is not the sum of the Output of its parts (unless Output is very unrealistically defined). Consider the example of the

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[1] Provided he can deal with Investment. A way of doing this is suggested in Chapter III, p. 33 ff.

antisubmarine airship.[1] The task of this airship is to find, track, contact and destroy enemy submarines; and the Output of the whole system may be measured in terms of "submarines destroyed" per unit time, or in other specified conditions. If the system is analyzed into four sub-systems ("find," "track," "contact" and "destroy"), and the probability of success for each of the sub-systems equals .50, .60, .70, and .30 respectively, then the probability of over-all success (submarines destroyed) is equal to .06, not 2.10. In other words, the Output of the whole system is the product of the Outputs of the four sub-systems, not the sum. (Examples are given later in the report of more complex interrelationships.)

We may also assume that submarines killed are linearly related to the Value of the system; that is, it is n times more valuable to destroy n submarines than one submarine. This is true so long as the enemy's submarine campaign remains dangerous to us; but if it is at present critically dangerous, and the development of the new system is expected to remove the danger below the critical level, the first n submarines destroyed by the new system may be considerably more valuable to us than the second n.

3. Constructional Approach

In the case of the antisubmarine airship, the Output of the system may be measured in terms of a single entity—rate of destruction of submarines--and this in turn may be related to the Value of the system in a fairly straightforward manner. Sometimes, however, this is not possible, either because it is not clear what elements of the Output of the system contribute to its Value, or because the relevant Output consists of many parts. In the former case, the historical approach may prove useful. In the latter case, some means must be found for combining all the elements of Output into a single criterion. This may be called the constructional approach, and has often been used.[2]

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[1] CHANNELL, R.C. et al. Human factors in the design of airships. Office of Naval Research, Technical Report SDC 641-2-9, 30 June 1950.(CONFIDENTIAL)

[2] CHANNELL, R.C. et al. Human engineering appraisal of the air control center of picket submarines. Office of Naval Research, Technical Report SDC 641-2-10, 30 December 1951. (CONFIDENTIAL)

Both the historical and constructional approaches demand definition of the mission of the weapon under consideration. For the historical approach, it is adequate to define the mission in such terms as "the support of infantry." For the constructional approach, however, much closer definition is needed, such as "to support the infantry by killing the enemy, destroying his morale, disrupting his communications and so on, this to be done by firing high explosive projectiles at his forming-up places, his chow lines, his command posts, and his roads." The mission must then be broken down into a precise series of submissions, in which the importance of each sub-mission is stated, and from which a set of required man and equipment characteristics for each sub-mission can be derived.

The importance of any sub-mission is the product of the frequency with which it can be carried out, and (in the military case) the damage inflicted on the enemy on the average each time it is performed. The "damage" term should actually be the value to oneself of the damage inflicted on the enemy. It will be seen that both of these are likely to be difficult or impossible to evaluate in any precise maner. Nevertheless, they are evaluated, consciously or subconsciously, in connection with every decision ever made to design, build, or modify equipment, and it is perhaps useful merely to bring out into the open the very flimsy foundation of such decisions.

It has often been considered sufficient to specify for a system its "most crucial role," and to attempt to maximize its performance of that without reference to any other role. Sometimes the investigator has been a little more ambitious, attempting to maximize performance of the most crucial role, and to improve the performance of other roles to the greatest possible extent without interfering with the primary role. This ignores the Cost associated with most facilities and improvements in facilities: for almost every improvement or gadget, something must be paid. In cases where the increased Cost is very small, this approach may work; but even there, it is not logically sound. Consider an equipment with four roles, a, b, c, and d. The roles have importances (measured on an imaginary linear scale) of 2, 1, 1, and 1. Role a demands that the equipment be as nearly completely silent as possible, but roles b, c, and d demand the maximum amount of noise. Should the equipment be made as noisy or as silent as possible? Clearly, the system designer must consider a number of possible solutions, with different balances of noise and

silence, and evaluate each in terms of its contribution to the Value of the super-system of which his system forms a part.

To do this on a purely logical basis will often demand greater expenditure of research effort than is justified, and in practice a non-logical intuitive evaluation is very frequently made. Fortunately, the differences between intuitive assessment and completely logical measurement of the importance of each sub-role, and the importance to each sub-role of each part of the system, tend to be small. This can be proved formally, but an example may make it clearer. The table below considers a system having four roles and seven parts. Reasonable importances, on a scale of 1 to 10, are assigned to each role in Column 2, and the importance of each of the seven parts to each role is given in Columns 3 through 9; these have been filled in from random numbers.

Column 1	2	3	4	5	6	7	8	9
Role of sub-system	Importance of role	Importance of parts a through g for each role						
		a	b	c	d	e	f	g
1	10	7	3	4	8	5	5	7
2	8	0	6	2	1	0	1	3
3	7	6	9	4	9	5	2	9
4	2	7	6	5	3	3	6	3

Weighting the importance of each part by the importance of the role, totalling Columns 3 through 9, and dividing by the sum of the importances of the four roles, we have the following total importances of parts a through g:

4.7 5.7 3.5 5.8 3.4 3.1 6.0

These are quite different from the most crucial role technique, which considers only role 1. Now suppose we have misestimated the importance of the roles and that instead of 10, 8, 7, and 2 they should

be 8, 8, 7, and 4. We should then have obtained the following total importances of parts a through g:

4.7 5.9 3.6 5.5 3.2 3.2 5.8

which are very similiar to the set of figures derived by weighting according to importances 10, 8, 7, and 2. Suppose now that we have misestimated the importances of the seven parts in each of the four roles by one-fifth in either direction, so that we ought to have filled in the body of our table thus;

Column 1	2	3	4	5	6	7	8	9
Role of sub-system	Importance of role	Importance of parts a through g for each role						
		a	b	c	d	e	f	g
1	8	8.4	2.4	4.8	6.4	6.0	4.0	8.4
2	8	0.0	7.2	1.6	1.2	0.0	1.2	2.4
3	7	7.2	7.2	4.8	7.2	6.0	1.6	10.8
4	4	5.6	7.2	4.0	3.6	2.4	7.2	2.4

We should then obtain the following total importances of parts a through g:

5.1 5.8 3.7 4.7 3.7 3.0 6.4

The results of the different degrees of refinement of method are given on the following page; they show that the average and the greatest deviation of the "inaccurate" methods 1, 2, and 3 from the "accurate" method 4 are:

Method	Average deviations	Greatest deviations
1	1.75	3.3
2	0.35	1.1
3	0.35	0.8

Method	Importance of parts a through g						
1. "Most crucial role," plus intuitive estimates of importance of parts for each role.	7	3	4	8	5	5	7
2. Intuitive estimates of importance of each role, and of the importance of each part for each role.	4.7	5.7	3.5	5.8	3.4	3.1	6.0
3. Accurate estimates of importance of each role and intuitive estimates of the importance of each part for each role.	4.7	5.9	3.6	5.5	3.2	3.2	5.8
4. Accurate estimates of importance of each role and of each part for each role.	5.1	5.8	3.7	4.7	3.7	3.0	6.4

The above example suggests that the following conclusions may be reached with regard to the constructional approach: The "most crucial role technique" should not generally be used in estimating the importance of a system, its parts, or the roles it may serve. An attempt should be made, instead, to measure or to estimate the importance of each role the system may subserve as well as the importance of each functional part of the system. It is not necessary, however, to measure importance precisely since, in practice, the results obtained with reasonable intuitive assessments do not differ significantly from the results obtained with very accurate measurements.

4. Transposition of Value and Cost

From the nature of the numerator of the criterion, Value minus Cost, it is evident that Value may be considered equal to "minus Cost,"

that is to Cost saved. This may offer a method of estimating Value reliably. An example in which this is done is given in Chapter III, p. 33 ff.

5. Two Special Cases of Value

Loss of equipment and its crew

A problem which frequently arises in the analysis of military systems is to determine the Value of a single ship, tank, or aircraft, together with the men who operate it. This is comparable with the problem of the Value of a human, studied by Bichowsky.[1] He considered the Value of a human to be equal to the sum of all the things he would have been able to produce in the rest of his working life had he not been killed. From this amount, his maintenance Cost for the whole of the rest of his life must evidently be subtracted. On this definition, the Value of the average human computed over his life time, must be low: over most of the world, the average human consumes in his life time as much as he produces, and when this occurs Value (on this definition) is zero, and the Value of about half the population would be negative. In the case of military equipment, a more reasonable criterion is believed to be possible.

The Value of any piece of equipment and its human operators is equivalent to the damage it is likely to inflict on the enemy during the rest of its life. By this equation, the Value of weapons which destroy either very mixed property (such as mixed ships' cargoes of food, clothing, raw materials and so on), or property which can be used for a number of purposes, can be measured in the probable dollar Cost of the destruction they will cause. A submarine is the best example. The Value to us of a single submarine--what we lose if that submarine is destroyed--is quite well measured by the average dollar damage which a single average submarine does to the enemy during its average life. In general, if the probability of the equipment successfully weathering an attack is increased by a Value p, (that is, from its orginal Value o to a new Value o + p) the Value of the system is increased by the ratio (o + p) / o, provided such equipments usually end their lives by enemy destruction rather than wear and tear or getting out of date. From the purely logical point of view, therefore, equipment is more expendable near the end of a war than at the beginning.

1 Unpublished. Carried on at Operations Research Office, Dept. of the Army.

Although in the case cited here it is reasonable to express Value in terms of dollar units, it should be recognized that dollars in some instances will be an oversimplified and inadequate measure of Value. For example, the equipment, property, etc., which is destroyed may have a strategic value to the enemy. In this case, given two factories, involving exactly the same dollar cost to the enemy, destruction of the one producing a much more vital piece of equipment will represent a more serious loss to the enemy and a greater gain or Value to us.

The Value of men of different ranks and abilities

ORO made some attempt to treat this problem in connection with the direction of propaganda to different segments of an army.[1] The treatment was a mathematical one, based on a number of reasonable assumptions about the chain of command on the one hand, and rank differences in intelligence and experience on the other. It appears likely that the Value of a man of rank m is of the order of one-half that of the total Values of all the men of rank m - 1 under his command. This statement should be regarded only as a general, order-of-magnitude guide.

C. Cost and Investment

1. Cost

The term "Cost" is used to refer solely to the operating cost of the system and, in many cases, can be simply and directly measured in dollars. However, there are at least two exceptions to this rule, both determined by the condition of the economy of the nation containing the system.

Consider the case of a nation with a large number of unemployed workers, who are able to work if a job is offered to them, and with supplies of raw material which could be developed and used by this

[1] See classified technical memorandum prepared by Operations Research Office, Dep't of the Army, Number ORO T-10.

force of unemployed labor. These men have to eat, wear clothes, and rent houses whether they work or not; and their total essential consumption of these items will hardly be increased if they spend their time digging coal, limestone, and iron ore out of the ground and using it to make steel. From the viewpoint of the nation, there is a theoretical possibility of getting something for nothing by putting these men to work. The theoretical possibility is never quite realized in practice because the men must be given some incentive to work, either in the form of increased supplies of this world's goods, or in the form of penalties for not working, which have a perceptible administrative Cost. But at any rate, the nation may get its extra steel production for a negligible Cost.

It is important in connection with design and optimization of military systems that such periods exist at the beginnings of most wars. The problem here is merely one of obtaining maximum Value from the men and materials, and Cost need scarcely be considered. Often, owing to failures of organization, such surpluses of labor and material may exist for limited periods during all phases of wars; and it is important to observe that they may be profitably employed on operations which would be quite unjustifiable on a dollars and cents basis, or on any basis, at other times.

Dollars also form an inadequate guide to Costs in the exactly opposite case--where the economy is so fully stretched that no man and no machine can be put to work on one job without being taken off another. Such economies usually lead either to inflations or controls. In comparing one system with another, it is usually true that a general reduction in the value of money will affect both systems in the same degree, so that the comparison between them will be unaffected by the progressive change in the values of the units in which they are measured. It sometimes happens, however, that the Costs of some items increase much more rapidly than those of others, and this may invalidate any comparison of the relative merits of two systems which does not take fairly accurate account of such differences.

If controls replace inflation, the systems designer will usually be presented, from a higher echelon, with a policy decision as to how much of what sorts of men and materials he may employ; and here again the former's problem is to maximize Value, without reference to Cost.

To summarize, then, dollars in many cases form an accurate and reliable measure of Cost. However, there are exceptional conditions:

a. During depression periods real Cost may be so low as to be negligible.

b. Controls and allocations may fix Costs permissible, so that the problem of Cost does not arise.

c. During periods of inflation, Costs of materials and men rise roughly in proportion to their scarcity.

The systems analyst, therefore, is faced, according to conditions, with the choice of considering Cost in dollars, maximizing Value with the men and materials he is allocated, or attempting to consider true Cost in rather less naive terms than the dollar. Many of his problems fall into the first two categories.

2. Investment

In the present analysis, Investment is distinguished from Cost by the fact that it is used before the system goes into production. It must, therefore, exist as the product of other systems before our particular system is built. Once spent, it cannot be used again except insofar as the physical items on which it is expended are general, flexible, and non-specific in nature. An example of a highly flexible expenditure is the operating cash balance in a bank; less flexible items are such things as buildings, trucks, machine tools, or generators; and highly inflexible items include such things as ammunition, for a particular caliber of gun, or a railroad track.

While a particular system continues to exist and to be fully used, the Investment made in it must be regarded as fully specialized and inflexible. Only after the useful life of the system is over does flexibility pay off in terms of reducing Investment.

From this discussion it will be seen that in an incompletely utilized economy, the Investment cost appropriate to consider in

systems design is the total initial investment less that part of it (if any) which the flexibility leaves usable after the life of the system.

In a completely utilized economy, where no unused goods or services are available for construction of the system, a new system can only be built at the expense of the continued operation of an existing one. Thus, the problem of criterion maximization resolves into a Value maximization for the lowest level super-system which contains both the proposed new system and the one(s) which will have to cease or reduce operations in order to allow the new one to be built.

D. Effect of Reliability on Cost and Value

The reliability of systems has certain effects on their usefulness. If a system breaks down, either partially or completely, certain disadvantages ensue. If the breakdown is incomplete, the Output of the system is lost for the time necessary to make repairs, and the repairs have a Cost. The former is to be subtracted from the original Value of the system, and the latter added to its original Cost. If the probability of such an incomplete breakdown is p_1, the Cost of repair is $\bar{r}$, and the time taken from normal operating time in order to effect repairs is $\bar{t}$, we must add $p_1 \cdot \bar{r}$ to the Cost, and subtract $p_1 \cdot \bar{t}$ from the Value. This, of course, is strictly true only of systems which are numerous: true for, say, a gun, because the absence of the fire of a single gun will rarely disorganize the operations of a larger unit. It would not be true of a system such as an aircraft carrier, whose loss or breakdown might prevent the successful operation of a whole fleet.

Increases in reliability can usually be bought, either by better--and generally more expensive--design, or by better and more expensive attention to maintenance. The reliability of many small components, such as electrical parts, and of some larger ones can be readily predicted; when this is so, the balance between loss due to too heavy expenditure on attaining reliability and too great loss by not achieving it can generally be approximated. The reliability of large components, with which the Service or industry has had little field operating experience, often cannot be estimated closely and, therefore, has to be ignored.

CHAPTER III

EXAMPLES OF SYSTEMS ANALYSIS AND USE OF CRITERION

It is highly desirable to translate the general considerations developed in the previous chapter into working suggestions for the benefit of those who design or do research on systems, and since the most difficult and most fully studied systems are military ones we shall deal primarily with these. The most useful method of presentation seems to be to give a series of examples,[1] showing in each case what could be done, and discussing the assumptions underlying the conclusions. We shall deal among others with several examples already employed and work them out in more detail.

The techniques of systems analysis are developing rapidly, and only the first few of the examples given show any adequate consideration of Value, Cost and Investment. The remainder merely exemplify techniques for studying performance or Output.

A. Use of the Value Concept

1. Comparison of Two Weapons Systems

Let us compare the Values of close air support and field artillery. At the period under review, both these formed part of the army. The Value of the whole army consisted of the sum of the Value of tactical air support, the Value of the artillery, and the Values of other parts of the army. To compare the Values of the artillery and the Air Force it is evidently unnecessary to know the Value of the whole army: which is fortunate, because no means are yet available for measuring it. It is reasonable, however, to assume that the Value of the whole army will increase from a low figure when the army makes little contribution to winning the war (all land campaigns lost quickly), through progressively higher figures when the "average" land campaign is slowly lost, the "average" land campaign is slowly won, and

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[1] Some will be actual studies, generally drawn from British sources, and some will be hypothetical examples.

all land campaigns are quickly won, to perhaps the highest figure of all when the enemy refuses to commit his forces to land action against our army.

The Value of the whole army, therefore, will increase continuously (though probably not linearly) with the rate at which the army wins land campaigns. It appears probable that the rate at which an army wins a campaign consisting of many battles could be measured, to a first approximation, by some such criterion as "miles advance on a front of given width divided by battle casualties sustained in making the advance." To determine whether or not it is a true criterion as well as a reasonable and probable one, we may determine whether or not amounts of support of various kinds (air, artillery, and other) are correlated with it: if they are highly correlated, it is probably a good criterion. In the interests of brevity and clarity, we may call our criterion "cheapness of advance." If the amount of any weapons system is negatively correlated with cheapness of advance, then either our criterion is inadequate, or the weapons system concerned has negative Value, or its Value is rendered negative in practice because its employment renders more valuable or bigger systems ineffective.

In a statistical investigation of World War II data, it was found that the majority of weapons systems tested were positively correlated with the logarithm of cheapness of advance, some as highly as 0.7; none were negatively correlated, and the one which was not correlated was judged, on other grounds, to be of somewhat doubtful value. Further statistical study showed that the different systems were scarcely or not at all correlated with one another, nor did they appear to be correlated with time over the 10 to 11 months chosen for study. There was also evidence that the use of the weapons systems caused the changes in cheapness of advance, rather than that the changes in cheapness of advance caused the variations in the amount of use made of the weapons systems. The criterion of cheapness of advance was, therefore, judged satisfactory for a preliminary comparison of the Values of different weapons systems within an army.

Since Value and Cost were to be measured in units not at present inter-convertible, it was necessary to compare the two systems either on Value provided per fixed dollar Cost, or dollar Cost of providing a fixed amount of Value. The latter was chosen. By a regression analysis

technique, a determination was made of the amounts of 1) air support and 2) artillery support necessary, per day, to double the cheapness of advance of an infantry regiment.

Suppose that the analysis of World War II data showed the following (imaginary) figures:

To double the cheapness of advance of an infantry regiment took, say, 10 aircraft sorties per regiment per day, or 4,000 rounds of 105 mm high explosive shell per regiment per day.

Investigations of Cost of each aircraft sortie, or each shell delivered on the target could be made, and are believed to be being made at present. Let us suppose they show the following figures:

One aircraft sortie costs $1,000.

One artillery shell costs $10 to fire into enemy positions.

To produce the same effect, as judged on the basis of "cheapness of advance," the relative Costs are thus:

Aircraft	$10,000
Guns	$40,000

We need not now put our Value and our Cost in the same units: it suffices to compare the Costs of the two systems for the same Value. On these (imaginary) figures, we should thus be justified in spending a bigger proportion of our defense dollar on aircraft, and a smaller proportion on guns than we did in World War II. However, we cannot say precisely how much more of the defense dollar should be spent on aircraft because: 1) as the number of aircraft increases, certain men and materials used in running them will become increasingly costly (how much more costly, how soon, is unknown); and 2) as aircraft increase in numbers, they will tend to be used on progressively less important targets. Somewhat similar considerations will be applicable in reverse to the guns they would displace, although we know at least that we cannot completely replace guns by aircraft if only because there are some conditions in which aircraft cannot fight at all, e.g., bad weather.

The way the defense dollar is spent should also be considered.. A very large Investment may be unattainable. On the other hand, since aircraft are more flexible than guns (i.e., can be used for such purposes as bombing industrial targets, carrying troops, etc.), not all their Investment cost should be counted in; something useful will remain when the need for close-support aircraft has passed.

The most realistic solution, on the considerations advanced so far, would seem to be to think in terms of doubling the existing ratio of aircraft to guns, and making provision for further operational evaluation of their new relative goodness when occasion arises.

One further source of uncertainty in this comparison has yet to be considered: the effect of both weapons must depend to some extent on new developments in design and tactics since the last war was fought, and on the cultural and tactical nature of the new enemy and the new terrain and climate. Estimates of the effects of these changes could sometimes be made on a realistic basis. World War II studies could be conducted over as wide as possible a variety of terrains, climates and enemies; military and maybe anthropological studies could suggest which way the new conditions of use would be likely to affect the comparison. For example, in the military studies, it might be relevant to consider that as tactical air support of land operations is a newer technique than support by artillery, it may be less well worked out, and show more room for improvement.

2. Use of Airships in Antisubmarine Warfare

Airships used in antisubmarine warfare may be regarded as land based (near suitable sea areas). They will carry out missions whenever conditions are deemed suitable, during which they will patrol sea areas or protect convoys, will search for enemy submarines, locate them, bring themselves into position for attack and then kill them.

The Value of antisubmarine airships will be a part of the Value of the Navy: the total Value of the Navy and the part of it ascribable to ASW airships are unknown. This is at present not important: we have to compare the Values of a number of possible ASW airship systems, and we do this by considering their function.

We shall assume that improvements likely to be made to the design, operation, and numbers available of these aircraft will not be so large that targets will become significantly rarer; that is, that Output and Value will be linearly related over the portion of the curve with which we shall have to deal. When the percentage of enemy submarine kills in a certain area reaches some particular amount, the enemy will avoid this area, and further improvements in killing power may be valuable only insofar as they may permit the redisposition of submarine killers to cover other areas. This critical percentage is likely, by analogy with other military operations, to be quite low: about 5 to 10 percent of submarines in the area. Therefore, if we assume that the proportion of enemy submarines in the area killed is 10 percent or less, we may say, without serious error, that the proportion of submarines killed will vary directly as:

a. The proportion of the area under surveillance at any one time.

b. The likelihood of any submarine in the area under surveillance being destroyed.

The size of "a" is in turn dependent on number of airships available for operational flight, size of total area, the size of the area covered by each airship at any moment and the proportion of each airship's operational flying time spent over the target area. The last depends in turn on the distance from the base to the search area, and the speed and endurance of the airship. The size of "b" will be proportional to the product of the following: probability of detecting targets, of locating them when detected, of tracking them successfully when located, and of killing them when attacked. These various factors may be symbolized as follows:

<u>Situational factors:</u>

n = number of airships available for operational flight

a = size of area to be protected

d = distance from airship base to search area

s = speed of airship

e = endurance of airship

f = time spent by airship in operational flight as a proportion of total time

Criterion for entire system

P = probability of killing a particular submarine

Criteria for sub-systems

A = instantaneous surveillance area of one airship as a proportion of a

D = probability of detecting submarine in A

L = probability of locating any submarine detected

T = probability of gaining position for attack of a submarine located

K = probability of killing a submarine attacked

Time over target will be f minus time spent in getting there and back, multiplied by number of trips. This resolves into $f - (f/e \cdot d/s)$ which equals $f - (fd/es)$. We may then write:

$$P \propto (n/a) \cdot (f - fd/es) \cdot (A \cdot D \cdot L \cdot T \cdot K)$$ [1]

The number of submarines destroyed could be increased X percent by any of the following increases or decreases in the parts of the system:

Increase of X% in n, A, D, L, T or K

Decrease of X% in a

Increase of $X/(1 - d/es)$% in f

and so on.

[1] This equation describes an individual system. For use with all systems of a particular type, probability distribution must be used.

We shall assume that n, the number of airships available, cannot be increased nor a, the size of area to be protected, decreased. Clearly changes in e, the endurance of the airship, at the expense of s, speed of airship, or vice versa, will have very little effect on P, the probability of killing a particular submarine. Moreover, changes in f, the time spent by the airship in operational flight as a proportion of total time, will only achieve importance if there are changes in the size of the area to be protected, the number of airships available, or the performances of the sub-systems. The possibility of improving the performance of the entire weapon more than twofold by operational changes in the situational factors is remote; but twofold improvement in the performances of each of the sub-systems will have a total effect of a thirty-two-fold increase in the probability of killing a particular submarine. From this we may see that the next step is to evaluate each of the sub-systems, i.e., detecting, locating, attacking and killing, to find what room for improvement exists. There is an upper limit of unity to the performance of each of these steps, and the further any one of them is from unity, the more likely it is to be able to be improved by a large ratio. We shall, therefore, examine each of them in order of their size. Suppose we found that:

A (instantaneous surveillance area as a proportion of size of area to be protected)	= 0.05
D (probability of detecting any submarine in A)	= 0.10
L (probability of locating any submarine detected)	= 0.95
T (probability of gaining position for attack of a submarine located)	= 0.90
K (probability of killing a submarine attacked)	= 0.25

We should examine and maximize them in the order A, D and K, and ignore L and T altogether because they are already near to their maximum: any increase in the probability of destruction of submarines achieved as a result of research, manufacturing, or training directed to increasing L and T would be likely to lead to a decreased value for the criterion for the entire system, because of undue increases in the consumption of dollars, man-hours, or scarce research effort.

A, instantaneous surveillance area, is evidently proportional to r^2, where r is the maximum range of the radar or other detection device.[1] Increases in the range of the radar by about 40 percent will, therefore, double A; doubling r will quadruple A and so on, provided 2r remains less than the minimum dimension of a, size of area to be protected. The possible adverse effects on e, endurance of airship, of the extra weight associated with increased r or by other increases in weight will have to be considered; but this can be done since e is a function of weight. It is possible, too, that r may affect D, probability of detecting submarine in A; this can be checked, and an X percent increase in A, or a $\sqrt{X}$ percent increase in r is exactly counterbalanced by an X percent reduction in D.

We now pass on to a consideration of D probability of detecting submarine in A. Since the range of the radar has been included already in A, D consists mainly of the probability that the radar operator will be watching the right place on his tube when the pip appears. A certain amount of information on the process exists, and it seems possible that many pips are missed because of a tendency for the eye to attempt to follow the sweep line in a rapid jerky motion. If this is so, possibilities are opened up for increasing probability of detection by preventing the eye from attempting this motion. This might conceivably be done by dividing the screen into a number of radial segments, alternate ones being exposed, so as to fixate the eye in each segment in turn. If this were found to increase probability of detection, a further doubling could clearly be achieved by providing a repeater and a second operator, the repeater having segments 1, 3, 5, 7, etc., blanked off, and the original having 1, 3, 5, 7, etc., exposed, and 2, 4, 6, 8, etc., blanked off. Further improvement might also follow from having further repeaters and operators, especially if care were taken (e.g., by separating them) to make them as uncorrelated as possible. However this may be, it is very important to attempt all possible ways of increasing D, probability of detecting submarine in A, before moving on to the less significant K, probability of killing a submarine attacked.

Consider K, probability of killing a submarine attacked. From our fact finding analysis, T, probability of gaining position for attack, seems to be a successful operation. K seems, therefore, to be a problem of effectiveness of the depth charges, including the effects of aiming errors. Would doubling the number of depth charges approximately double K? Are they set for the right depths? Are they individually

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[1] Since the surveillance area is circular, and the area of a circle is proportional to the square of its radius.

powerful enough? Suppose we find that the diameter of effect of each depth charge is 25 feet, and that they are dropped at fifty-foot intervals. Provided that the fifty-foot-interval stick all lies in the region where the submarine has a high probability of being, the best solution is probably to double the number of charges dropped, keeping the stick the same length. If the stick is long compared with the zone in which the submarine probably is, the solution would be to shorten the stick rather than increase the number of charges dropped. If the stick is short compared with this area, either the stick should be lengthened by addition of more depth charges, or the aiming errors should be reduced. Knowing the radius of effect, stick length and interval, and the aiming errors, we can calculate the effect of any combination of methods on the criterion for the entire system.

Cost has now to be considered for each of the improvements suggested as a result of analysis and measurement. Some might have practically zero Cost; for example, changes such as alteration of the stick interval or the depth charge setting. Some would have very low Cost, such as addition of radar repeaters for use by crew members not otherwise continuously employed; it is sufficient in these cases to state that Cost is minute, and not to consider it further. Increasing the range of a radar set, on the other hand, is liable to be expensive, and would probably have to be worked out in conjunction with the total radar set production and allocation position, and a policy decision made by the officer responsible. This decision is not generally considered the province of the systems analyst, nor is he likely to be the best person to make it.

This example should be of particular interest to systems analysts and human engineers because it shows how a careful analysis of the present behavior of the system, together with a previous analysis of the general system "man-radar," enables the systems researcher to make suggestions which are likely to result in major improvements to the system at little Cost. In the example used, the theoretical performance of the system was not being attained because of human limitations, and slight redesign, to take account of human factors, was likely to mitigate this bottleneck.

3. Early Warning of Air Attack

In answering the question, "How much early warning of air attack should a fleet be given?" let us consider the relative merits

of two possible versions of the same system. The first provides enough early warning for all but one of the attacking planes to be intercepted and shot down. The second provides enough extra early warning for all but one of the attackers to be shot down, and also for a single pass to be made at the last attacker.

Let the usefulnesses of the two versions be:

Version 1	Version 2
$U_1 = \dfrac{V_1 - C_1}{I_1}$	$U_2 = \dfrac{(V_1 + V_2) - (C_1 + C_2)}{(I_1 + I_2)}$

Now, the disadvantage of letting the last plane through is:

$$E_b + P_s \ (E_s + S)$$

where:

E_b = the expense to which the enemy would be put in replacing the last attacker had it been shot down.

P_s = the probability that the last attacker will sink one of our ships if we do not shoot it down.

E_s = the expense to which we should be put in replacing that ship if it were sunk.

S = the strategic value of the ship at this time.

If $\underline{k}$ be the single-pass kill probability of our fighter against the attacker, then:

$$V_2 = k \left[E_b + P_s \ (E_s + S)\right]$$

The extra running cost (C_2) entailed by the extra pass will consist only of a small amount of gasoline, ammunition and wear and tear. It may be regarded as negligible, i. e., $C_2 = 0$.

Examination of the speed-time-distance relationships in the system reveals that I_2 is the Investment (I_p) associated with a single extra early warning plane. That is, $I_2 = I_p$.

The usefulness of the second version now becomes:

$$U_2 = \frac{V_1 + k\left[E_b + P_s\ (E_s + S)\right] - C_1}{I_1 + I_p}$$

We may move the term I_p to the numerator by amortizing the term by dividing it by its probable life (in raids). Let its probable life be $1/P_d$, where P_d is its probability of being destroyed in any one raid. Then,

$$U_2 = \frac{V_1 + k\left[E_b + P_s\ (E_s + S)\right] - C_1 - I_p \cdot P_d}{I_1}$$

and:

$$U_2 > U_1 \text{ if } k\left[E_b + P_s\ (E_s + S)\right] > I_p \cdot P_d$$

That is, if:

$$kE_b + kP_s\ (E_s + S) > I_p \cdot P_d$$

it is possible to show that:

$$kE_b > I_1 \cdot P_d$$

and that:

$$kP_s\ (E_s + S) \gg I_p \cdot P_d$$

Consider first kE_b. The AEW plane and the enemy bomber will be very similar aircraft, so that $E_b \sim I_p$. Analysis of the system shows that $k > P_d$. Hence, $kE_b > I_p \cdot P_d$, and the second version of the system is better than the first.

Now consider the terms $kP_s(E_s + S)$ and $I_p \cdot P_d$. Study of the dollar costs of ships as against aircraft, particularly prime targets such as capital ships, shows that $E_s + S > 10$ or $100\ I_p$. Hence, we must show $10\ kP_s > P_d$; and a consideration of the probabilities in the system being considered shows this to be true. Therefore, the conclusion to be reached is that $U_2 \gg U_1$, which means that the system should be designed to give the most early warning that the fleet can use.

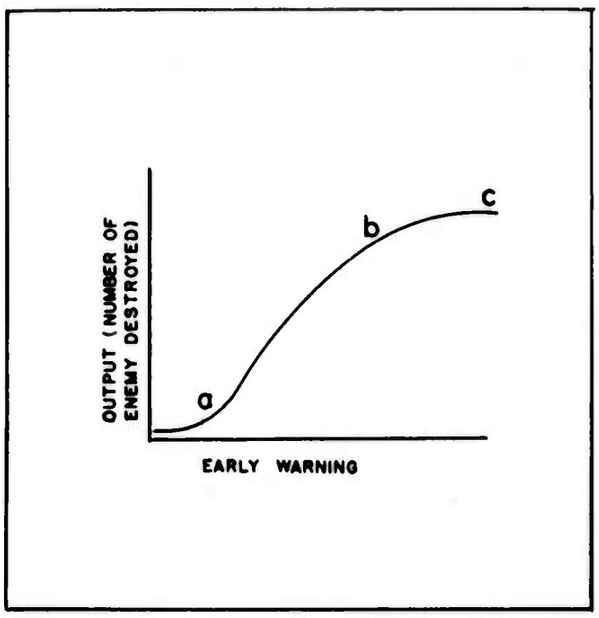

Figure 1. Relationship between output, in terms of number of enemy destroyed, and early warning.

This example is of particular interest because it gives a result very different from that which would have been achieved by considering Output and Cost instead of Value and Cost. Output, in terms of number of enemy destroyed is in this case related exponentially to early warning, as in Figure 1.

Early warning is directly proportional to Cost. Development of the best system on this basis would have involved choosing some system between a and b in the diagram. Consideration of Value, however, leads to the choice of a system to meet point c.

4. The Level of Crew Performance and the Use of ASW Weapons

The object in this example is to set an economic standard for crew performance and to show how to bring it about. Here the fundamental postulate is that training takes time, money, men, materials, etc., but leads to a reduction in radial error (re). This, in turn, increases the kill probability (k) and results ultimately in a saving of money, etc.

Let C be the Cost of the ASW operation of the Navy over a long specified period. Let c be the number of submarine contacts achieved in the same period. Let C_1 be that part of C incurred solely on attack runs. Then:

$$\frac{C-C_1}{c} \gg \frac{C_1}{c}$$

The Value of ASW operations is a linear function of $P_c k$ when P_c is the probability of making a contact (provided we are not running out of either enemy submarines or U. S. ships). Over a long period of time, the value of the ASW operations is, in fact, proportional to ck or K, the number of kills.

If $C-C_1 \gg C_1$, then economy demands that kill probability (k) be maximized rather than the number of submarine contacts (c) increased by adding new patrols and men. It is also self-evident that P_c should be increased by all means short of adding new patrols. Thus, our concern is with k, and there is a clear case for trying to maximize it. One way to do this is by better training.

Training Cost

The first logical step is to construct a set of curves relating the Costs of different amounts of different types of training to different re's. A set of hypothetical curves is given in Figure 2.

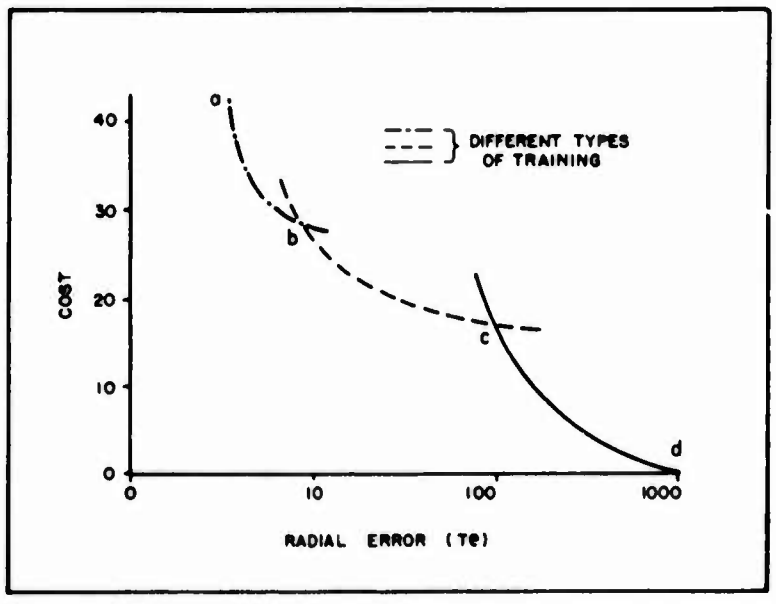

Figure 2. Hypothetical relationship between cost of training and its effect in reducing radial error.

The cheapest training, as shown by this simplified set of curves, would be that delineated by the inner boundary, a-b-c-d. The Costs should then be translated back to so many weeks at primary school, so many on the attack trainer, etc. If a value could be determined for optimum re, a logical syllabus could thereby be constructed from Figure 2.

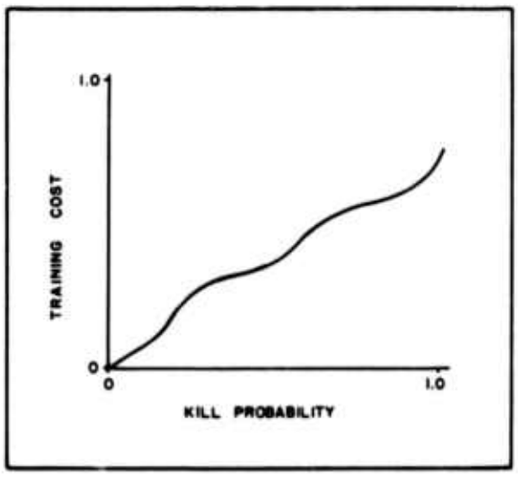

Figure 3. Hypothetical relationship between kill probability and training cost.

Optimum re — Let us transform training Cost into units of "value of a submarine," which in turn is equal to the dollar value of the ships and men it may be expected to sink in its life (see p. 20). Let us also transform re into units of kill probability (k). We then have a curve (Figure 3) relating Cost of training to Value of training, both measured in submarine units. We must reccognize, however, that other costs besides training are involved in attacking submarines.

We wish to determine the best level of training to attain, and this means determining Costs and Values for a set of possible levels of training. It also means adding in other operational Costs, $C-C_1$ and C_1.

Thus, in Figure 4 we show Cost ranging from 0.0 to 1.0 "submarine value," and kill probability (k) ranging from 0.0 to 1.0. The line b b b (joining Cost = 1.0, k = 1.0 to Cost = 0.0, k = 0.0) is a break-even line. Any system operating to the upper left of this line is "losing money" in an amount equal to its distance above b b b; and any system operating to the lower right of the line b b b is similarly "making money."

Let line $C-C_1$ represent the cost of making a single contact. Line C, placed a distance of C_1 above this line, represents the cost of a single killing run. This run has no value unless $k > 0.0$; and to make $k > 0.0$, training is necessary. We, therefore, draw a a from Figure 3, so that the points along a a represent the costs of various likelihoods of killing a submarine after a contact.

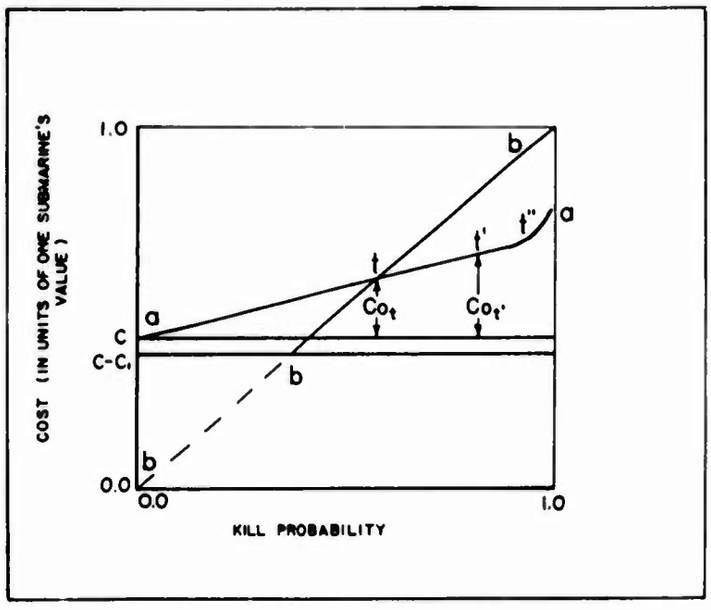

Figure 4. Economic and uneconomic levels of training.

Line a a crosses line b b b at t. Operations represented by the line a t are unprofitable by the vertical distance of a t above b b b. Operations t a, such as operation t', are profitable by the amount their cost falls below the break-even line b b b. Thus, training must be at least as good as t, costing Co_t, for the ASW operation to pay off.

Conclusion The amount of training to give is such that its position on line a a is a maximal amount below line b b b. Such a point might be t'' on Figure 4. The cost of this training (Co_t'') should be read from the curve and applied to Figure 2 to produce a syllabus.

B. Analyses in Terms of Performance

1. Errors

Human operators of machines can make the folowing types of error:

a. Quantitative: reading the wrong number on a gage, or setting wrong range on a range drum.

b. Qualitative: doing the wrong thing, such as reading range instead of deflection.

c. Errors in time: allowing too long (or less often too short) a time to elapse between two operations.

d. Sequential errors: performing operations in the wrong order, for example, cross-levelling a gun after making the final adjustments for line and elevation instead of before.

e. Errors of omission: leaving out operations or figures.

Sound general theories exist regarding the effects of quantitative errors in a number of steps in the same operation, and regarding the way errors-in-time build up. There are at present no general principles appropriate to errors of the other classes: each example must be treated and analyzed as a special case.

The build-up of quantitative errors

The build-up of quantitative errors is one of the most universal problems in systems research, has been well worked out in many cases, and is fundamentally straightforward. The main factors to bear in mind are: 1) Errors may arise either from the machine or the man. 2) Variances are additive; so are the squares of probable errors and average errors. 3) Errors may be random fluctuations about the mean position, or systematic deviations of the mean from its true position. Since the effects of these errors are rather different, and since they can usually be reduced by different methods, it is desirable to distinguish them from one another. 4) The ultimate importance of errors in military systems is usually that they tend to cause a projectile to miss its target. This can always happen in two planes and, unless the ammunition is impact fuzed, can happen in three. The total chance of hitting, $\underline{P}$, is the product of P_1, P_2, and P_3, the chances of hitting in each of the three planes. 5) Accuracy is often bought at the expense of time, as well as its usual dollar and manpower costs. 6) Scale reading problems often entail a proportion of gross errors, which need treatment separately from the normal fluctuations.

The usual statistical formula for combining a number of errors is:

$$\sigma_t = \sqrt{\frac{N_1 (M_1^2 + \sigma_1^2) + N_2 (M_2^2 + \sigma_2^2)}{N_1 + N_2} - M_t^2}$$

where N_1 and N_2 are the numbers of observations in the two samples, M_1 and M_2 the means of the two samples, with σ_1 and σ_2 as the respective standard deviations; the subscript t refers to the combined sample. In analytical work, we may frequently have $N_1 = N_2$, and $M_1 = M_2 = 0$, enabling the simplified formula:

$$\sigma_t = \sqrt{\sigma_1^2 + \sigma_2^2}$$

to be used.

(1) Simple sight and gun problems. Let us assume that the problem is to increase the Value of a gun laid by a sight by increasing its round-to-round accuracy. The first essential for economical research will be to measure the error from the two sources, sight and gun, separately. Suppose we find, which is a realistic case, that the error due to the sight has an average value of 0.3 mil, and that of the gun an average value of 1.0 mil. Then the total error of the sub-system gun-and-sight is:

$$\sqrt{0.3^2 + 1.0^2} = \sqrt{0.09 + 1.00}$$

or

$$\sqrt{1.09}$$

or

about 1.05 mils.

Evidently complete elimination of the errors of the sight would have a negligible effect on the total error of the sight-gun combination. Money etc., spent on improving the sight would be almost wholly wasted, and the criterion, Value minus Cost divided by Investment, would be reduced rather than increased for this reason. Attention must, therefore, be focused on the gun.

Let us take this problem one stage further back, and consider the Value likely to be achieved by reduction of the gun error. The purpose of the gun is to hit a target. The extent to which it can do so will depend on the relative magnitude of the error of the gun-sight-man combination and the size of the target.

Suppose that the target is an enemy tank head on, so that it may be regarded as a square vertical area measuring three yards by three yards. There will be a range beyond which there is no point in firing at the tank, either because there is negligible chance of hitting it, or more probably, because it will not be penetrated if hit. The target will subtend three mils square at 1,000 yards, 1 mil square at 3,000 yards, etc. Construct a graph showing the single shot probability of hitting as a function of range, when the range is known: this is done simply by means of probability tables, remembering that the chance of a hit is the product of the probability that the shot has the correct azimuth and the probability that it has the correct elevation. Construct another curve showing the probability that a single hit will destroy the tank, again as a function of range. A picture rather like Figure 5 will be obtained.

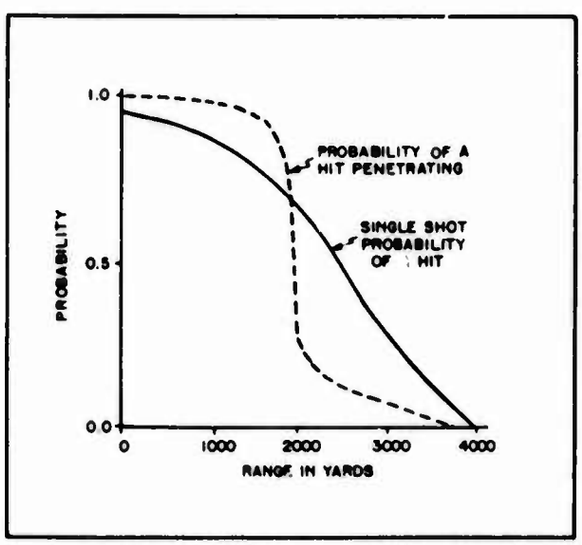

Figure 5. Probability of destroying a tank as a function of range.

The product of the two curves gives the probability of destroying the tank as a function of range.

In the case we have drawn, there is no point in attempting to improve accuracy, since the probability of hitting is very high throughout the range at which the gun can defeat the armour. Money, time, and effort spent on this would increase Cost but not Value and, therefore, reduce the criterion. If the dotted line (armour penetration) were moved a thousand yards to the left, the systems design

problem, if it existed, would be to increase the penetration performance of the gun. The problem might not exist--for example, it might never be necessary to open fire at ranges over 1,000 yards--or might be insoluble, if increased penetration carried with it compensating disadvantages. If the penetration curve were moved 1,000 yards to the right, a case might be made out for increasing the accuracy of the gun. The case would not be a very strong one, however, since the area under the curve of probability of destroying the tank as a function of range would not be increased very much. This statement might be modified if the range from 2,000 to 3,000 yards could be shown to be tactically of much greater importance than the ranges less than 2,000 yards.

Is there any advantage to be gained by increasing the penetration so that the curve of penetration is moved 1,000 yards to the right? Clearly this would enable us to open fire successfully at longer range, and might enable us to prevent the enemy from getting close enough to us to penetrate our armour. This was substantially the case in the Western Desert campaigns of 1941-43: the British tanks were outgunned by the German Pz III and Pz IV, as well as by the redoubtable 88 mm gun. On the other hand, use of a larger gun or heavier ammunition means less guns, less ammunition, and a lower rate of fire. It is normal during a war for both the size of guns and the thickness of armour to increase. A systems analyst, before deciding on the best gun for the job, would wish to know the extent to which the enemy could up-armour his tanks to defeat various possible guns. Use of a gun which was initially too big might be justified on grounds of morale, the possibility of enemy up-armouring, and avoidance of breaks in production when a new and bigger weapon became not only desirable but necessary.

The curve in Figure 5 represents probability of hitting when range is known. The ability of the unaided man to estimate range, and the performance of men using various kinds of range finders are among the most fully worked out fields of human engineering. The knowledge we already have indicates that (in land fighting) an unaided man estimates range to a mean deviation of 25 percent of the range, almost independent of training and selection; and a meter base range finder of 14 - times magnification has a mean deviation of $14R^2$, where R is range in thousands of yards, the error being increased inversely in proportion to base length and nearly inversely in proportion to magnification.[1] This information enables the systems analyst to make intelligent decisions as to whether a rangefinder is needed and if so, what kind it should be.

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[1] That is if we double base length we halve error, and if we double magnification, we reduce error considerably, but not quite to half its previous value.

The use of a rangefinder also has implications regarding speed of action: these are dealt with on page 51.

It will be seen that so far we have first considered one system (laying and firing a gun), have gone up the hierarchy to a super-system (hitting the target), and have then combined this super-system with others at the same level (e.g., penetration of targets) in order to study a still higher system (destruction of tanks by gunfire). No reasonable solution to the first system was possible without these steps up the system hierarchy, and without assumptions, for example, about the Cost of guns, sights, ammunition, and research and development, and the Value to us of tanks destroyed.

(2) Sight and gun problem with errors different in different planes. The errors in the vertical and horizontal planes tend to be different. This is because the engineering equipment for moving the gun is different; the methods of determining when the gun is correctly laid differ (e.g., telescope reticle for line, bubble for elevation); and,for example, muzzle velocity, ballistic coefficient and range estimation affect the vertical plane almost entirely. It has also been found that with stationary targets, vertical errors are almost always greater than horizontal ones, but with moving targets they are often less.

If the probability of a round having a sufficiently correct elevation to hit the target is small (say, 0.20) and the probability of line being sufficiently correct to hit is large (say, 0.80) there will be little increase in probability of actually hitting the target unless efforts are concentrated on the smaller probability. In our example, the total probability is 0.20 x 0.80, or 0.16. An equal percentage increase in the probability in either plane will have the same effect on the total probability, but equal percentage improvements will usually be easier obtained in the case of the smaller probability, and much greater percentage improvements will be possible. In our case, the greatest conceivable improvement in line accuracy would only increase probability of hitting by 25 percent, but the greatest conceivable improvement in vertical accuracy would lead to a 400 percent improvement. The system's owner will usually get more Value for his money by concentrating on the smaller probability.

In two dimensional problems (impact fuzes) range errors are normally compounded with vertical errors. This can be done by means of firing tables.

The probability of hitting a target is a function both of the size of the target and the size of the errors. If the width of our target were reduced to one half, the probability of being sufficiently correct for line would be reduced from 0.80 to a little over half this value. If its height were doubled, the probability of being correct for elevation would be a little less than doubled. Exact values in any specific case are given in probability tables. It will be seen that we are not interested in accuracy as such, but only in accuracy so far as it affects hitting the target, and in hitting the target only in so far as a hit will destroy or neutralize it, and in its neutralization or destruction only in so far as this is of Value to us.

(3) Sight and gun problems with systematic, semi-systematic and random errors. A sight-gun combination may have the following sources of error in elevation, among others:

Type 1. If the gunner repeats his lay on many different occasions, he will not always lay the gun at precisely the same elevation: this is a random error of laying.

Type 2. The gunner may tend always to lay his cross-hair a little above his target, or his bubble slightly to one end of its tube: if he does, the mean lay he makes will not tend to approach more and more nearly the correct lay. This may be called a systematic error.

Type 3. If the systematic laying errors of a number of gunners are measured, they will not all be the same: there will usually be a random deviation of systematic laying errors.

Type 4. The range which the gunner has been given for the target may be wrong. So far as fire at this particular target is concerned, this will behave like a systematic error. But not all gunners, nor all targets fired at by the same gunner, will show the same systematic error. So far as fire in general is concerned, therefore, this error will behave like a random one.

Type 5. The gunner's particular range scale or quadrant may be incorrectly engraved: this type of error will behave like 4 above.

Type 6. The original firing tables and/or jump measurements may have been incorrect, so that all range scales and quadrants may tend to have an error of a particular amount in a particular direction.

What we do with each source of error depends on the precise question we are trying to answer. For example, the destruction which all gunners firing all guns at all targets can cause will depend on the sum of the squares of errors of types 1, 3, 4 and 5. The effect of error 6 will be to make all that class of gun tend to fire off the target. Evidently it pays to put a great deal of effort into correct calculation of firing tables and corrections, because errors therein show their effects every time any gun is fired. The error of a firing table can be reduced to very small amounts by expending on its production a lot of ammunition and a lot of effort.

Systematic errors may often be removed by zeroing. The use of coincidence rangefinders offers a good example of this process and its effects. If a number of settings of a coincidence rangefinder be made by the same operator on each of a number of different targets at different ranges, it is found that they will have a standard deviation whose magnitude is inversely proportional to the base length and to the magnification. Any single reading with a one meter base x 14 rangefinder will thus have an error of about 10 to 12 R^2 from the average which would have been obtained by a long series of readings under these conditions. If the operator zeros his instrument by taking a target at known range, setting coincidence on to it, then adjusting his range scale till it reads the known range to the target, the zeroing process itself will be in error by an amount also equal, on the average, to 10 or 12 R^2. The total error of a single reading from the true range will, therefore, be the square root of the sum of the squares of the two errors, or about 14 to 17 R^2. If, however, the operator bases his zeroing adjustment not on one, but on a series of readings on his target of known range, he may reduce his zeroing error to almost as small an amount as he wishes, since it will be inversely proportional to the square root of the number of readings he makes. Since some of the error zeroed out will be that due to imperfections in his own eyes or methods of operation, a zeroing operation carried out by operator A will tend to be not quite correct for operator B.

The familiar gunnery process of getting a round on to the sea or ground in the neighborhood of the target, and correcting the center of impact onto the target by sensing fire or bracketting, is also in a way an example of zeroing since it removes systematic errors due to incorrect survey, incorrect sight setting, changes in calibration of gun, variation in powder lots, and stale meteorological information. It differs from true zeroing in that it contains a correction for errors made in measuring range, line and metro for this particular target, so that it is less completely applicable to other targets.

(4) Treatment of gross errors. In addition to making small random fluctuations about a true scale reading or a true lay on a target human operators make mistakes. Philosophically, we say a man makes a "mistake" when, if he went over his reading or calculation again with an expert, he would realize he had been wrong; we say he makes a random error if, on repeating his work, he still considers it correct. This definition is a very faulty one, being rather impractical to work with, and not quite diagnostic, but it has the merit of giving a picture of what is meant by a mistake. In practice our criterion of what constitutes a mistake will be very variable: no one criterion appears to be universally applicable in the sense that it gives universally a reasonable delimitation.

When mistakes are rare--of the order of one or two percent--we may use the fact that, in a normal distribution, errors greater than three standard deviations will be exceeded only thrice in a thousand times (0.3 percent). We are fairly safe, when mistakes hav a true frequency between about one and three percent in calling all deviations greater than three standard deviations "mistakes." If the tru incidence of mistakes were much less than one percent, use of this method would lead to considerable overestimation of their frequency by addition to them of the 0.3 percent of large normal variations. If the true proportion of mistakes exceeds about three percent, ordinary meth of calculating the standard deviation lead to considerable overestimate and hence underestimates of the frequency of mistakes. Sometimes, wh several sets of data on the same problem exist, some of the mistakes c be thrown out of the variance calculation by ignoring first the biggest errors, and then progressively smaller ones until the variance left is homogeneous between sets. The three sigma limit is then calculated from this homogeneous variance.

It is sometimes profitable to plot a histogram of the distribution of errors, since breaks in the curve become apparent by this means and offer a reasonable criterion for distinguishing between mistakes and normal random error. Usually it is best to plot the full curve both sides of the mean, since a marked asymmetry could obscure the breaks.

One or both of these methods of distinguishing and defining mistakes may lead to an "unreasonable" answer. For example, if a man has a millimeter scale, graduated in single millimeters, easily visible to him, and he is required to read the length of a clearly defined line to the nearest millimeter, it should not be possible for him to make a random reading error much greater than half a millimeter. Anything more than, say, 3/4 millimeter must be a mistake, whatever the statistics say. If the distribution within the range of plus and minus 1/2 millimeter is studied for the situation of many men measuring many lines, the distribution will generally be found to be rectangular in form, because the size of the reading error is dependent on the exact length of the line, i.e., on whether or not it contains an exact number of millimeters.

Not only are mistakes troublesome to identify: they also lead to major difficulties in evaluation. Some of these difficulties are practical ones, and the remainder statistical ones, but none the less real. As an example of the practical difficulties of evaluation of mistakes, consider the case of an artillery officer reading a map for the purpose of putting down map fire on a target. If his target is 400 yards square, and he makes a mistake of 500 yards in reading his map, he will miss his target and may not discover his mistake until a long time afterwards. If he makes a mistake of 1,000 yards, he will miss his target no more completely, but his mistake, being bigger, is more likely to be spotted by himself or someone else. In this case, it would be better to make a mistake of 1,000 yards than one of 500 yards.

The statistical difficulties arise mostly from the fact that normal methods of computing variance and standard deviation assume normality in the population. A distribution flattened by inclusion of substantial numbers of large mistakes causes variance to be overestimated to an extent which may be very serious. No fully satisfactory method for adding in the contribution of mistakes to normal errors has yet been proposed, but various compromises are available which are appropriate

for some problems when carefully applied and interpreted. If it appears likely from the data that mistakes are very important, a technique should be used which deliberately underestimates them. If this method confirms their importance, this evaluation is to be regarded as well established in the sense that it is clearly not an artefact of the methodology. A suitable technique for this purpose is to calculate the mean deviation due to mistakes (the product of their frequency and their average size), divide it by 0.7979 to convert it to the standard deviation, and square the result to get the equivalent variance. This variance may then be added to, or compared with, that derived from the random variation.

If, on the other hand, it appears likely that the mistakes have little importance, a technique may be used which is known to overestimate their significance: the normal method of calculating the variance as the mean square deviation may be employed. If, even after this deliberate overestimate of the effect of mistakes, they appear relatively insignificant, we can be on firm ground in neglecting them.

Another method has been used to demonstrate the importance of mistakes in the military problem of predicted artillery fire. In this technique of gunnery, about eight different processes are carried out in order to determine the range and deflection to be set on the guns. If any of these processes contains an error greater than half the size of the target, the mission will be unsuccessful. We may consider a typical gun, a target of average dimensions, and a normal firing range, and determine for each process the proportion of occasions (on a scale from 0 to 1) on which the calculations and readings contained errors smaller than half the target dimension. The proportions are then multiplied together. This gives a satisfactory estimate of the proportion of times the target will be engaged, and its difference from unity gives the proportion of occasions on which we may expect mistakes in one process or another to prevent its engagement.

A compromise between the mean deviation method of estimating variance and the mean square deviation method has been suggested to give a method of estimation less biased than those two. The process is to count and exclude all errors big enough to make the process concerned entirely ineffective, to sum the squared deviations of the remaining errors and to divide it by the total number of observations including the (discarded) very large errors. This method cannot be recommended. A more rational modification of it might be as follows:

discard and count the very large errors; calculate the mean deviation and hence the variance of the rest, then multiply the variance so found by the ratio, which will be greater than unity, of the total observations to the total observations less the number of gross errors discarded.

The build-up of errors of time

If a system consists of n links, and the time delays at the links are t_1, $t_2 \ldots t_n$, with variances s_1^2, $s_2^2, \ldots s_n^2$, then provided the delays are uncorrelated, the total mean time delay is the sum of $t_1 \ldots t_n$; the total variance of time delay is the sum of $s_1^2 \ldots s_n^2$. In many cases, e.g., operating railroads, this is not an adequate treatment because the occurrence of a delay at one point may increase the likelihood of a delay at another. In systems containing highly motivated human beings, the reverse may be the case: a time delay at one point may put all the operators in the other links "on their toes" to such an extent that the original delay is either compensated by later speeding up, or even overcompensated. The sort of system where the occurrence of error at one link tends to cause greater delays at subsequent links may be called unstable, and is characteristic of organizations in which the traffic on the system is heavy enough to need careful scheduling, or of organizations where operator morale is poor. The compensating "stable" type is found where the communications or other network is capacious enough for careful scheduling to be unnecessary and/or human operator morale is good.

Errors of time are often translatable into quantitative errors by considering the performance of the lowest system containing both errors. Two examples will be given in the discussion of the interrelationships of speed and accuracy.

Qualitative errors in communications systems

If a communications system consists of n links, and the probability of a message being correctly transmitted over link 1 is p_1, over link 2, p_2, and over link n, p_n, then the probability that the message will pass all links correctly is the product of $p_1 \ldots p_n$.

2. Interrelations of Speed and Accuracy

Trading accuracy for speed

For system optimization, accuracy may have to be sacrificed to speed. An interesting example of this is a fire control system which was worked out theoretically for tanks by the British Ministry of Supply. The problem was as follows. One tank "sees" an enemy tank. Both are stationary and at a range of 1,000 to 2,000 yards. Neither tank knows whether he has been "seen" by the other or not. Tank A has to choose whether he will measure range with a rangefinder, thus taking time but ensuring a hit on the first shot. If he uses a rangefinder, tank B, who may have seen him, has an excellent chance of killing A before he fires. If A or B fires and misses, he will probably give away his position. If we know the chances of hitting with the first, second, third, etc., shots, with and without measurement of range with a rangefinder, and also the times taken to measure range, and to load, sense fire, correct, relay and fire again, and the chance that firing will give away position, the optimum solution to the problem is calculable. The technique used is to make up a series of timetables, for each tank, based on the several alternative assumptions and the two methods, in which the chance of survival of each tank is calculated after each round fired at it by the other. The fact that the engagement consists of a series of crises (the shots fired) small in number and short in duration makes this problem rather intractable to elegant probability mathematics. It can also be checked by trials using subcaliber ammunition, although this was actually not done.

We may well find, with the kinds of rangefinders and fire contr systems and ammunition we possess, that unless A is fairly certain he has not been seen by B he should estimate range instead of measuring it, to save time. If A is fairly sure he has not been seen, it will be best for him to use a rangefinder. If he does not use a rangefinder, and miss with his first shot, he must fire a second and a third shot as soon as pos sible in order to survive. An analysis showed that time here could be saved by not waiting to sense fire and consider what correction to make, but by going up one tank-height for the second shot and down two tank-heights for the third. Automatic loading and relaying also become important in order to save still more time. Means of preventing gun flash would also be important. It is interesting to observe that this study mad use only of data on human performance. The solution reached was to re place two human activities by machines and one other by precalculation.

[redacted]

Speed and accuracy in gun stabilizers

The function of a gun stabilizer is to make the gun continue to point in the same elevation and bearing with respect to the earth whatever the motion of the gun platform. It is sometimes convenient from the aspect of engineering to build the stabilizer in two functional parts: one to keep the gun within, say, plus or minus two mils of the target, providing tracking is correct; the other to keep the sight within, say, half a mil of the target, together with a device to permit the gun to fire only when it is within half a mil of the sight line. The time taken for the gun to fire after the gunner presses the firing switch will be determined by the frequency with which the gun hunts across its stabilized zone, and the ratio of the area within which the stabilizer keeps the gun (16 square mils) and the area within which the gun will fire. The area within which the sight is stabilized will be one square mil, and this will always be in the center of the larger 16 square mil area.

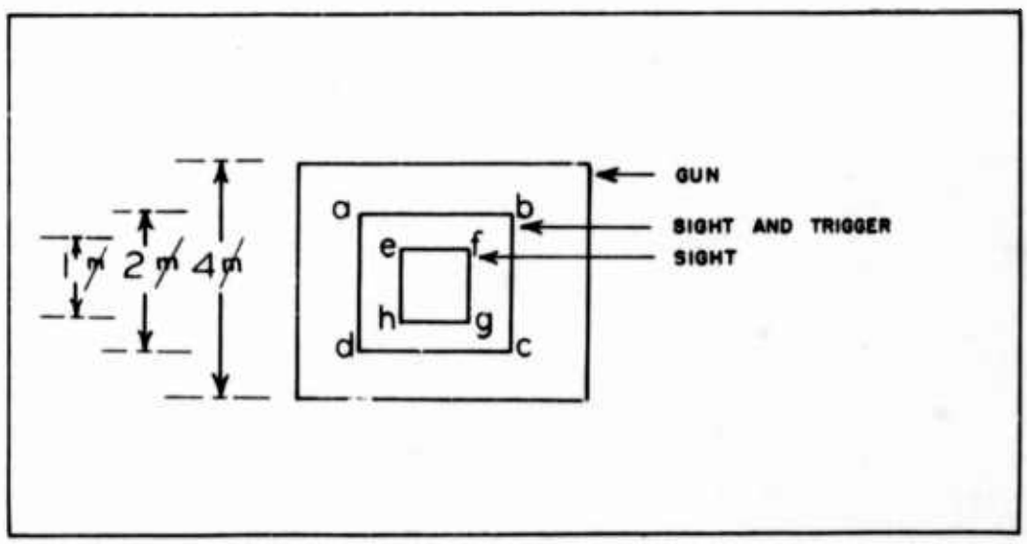

Figure 6. Areas of freedom of gun, sight and trigger.

[redacted]

When the gun is outside the area a b c d, it cannot fire at all. The proportion of time the gun spends in this non-firing area will be determined by the ratio of the whole area (16 square mils) to the firing area (4 square mils). That is, for three-quarters of the time, the gun will certainly be unable to fire. During the remaining one-quarter of the time, the gun will be within a b c d, and can fire if it is within a square of one mil side centered about the present position of the sight line. The proportion of this remaining one-quarter of the time that the gun will be within any one square mil is again one-quarter, so that of the total time for which the gunner, thinking he is on his target, presses the firing switch, the gun will fire only 1/4 x 1/4, or 1/16 of the time. The fact that the gunner will recognize that he is on his target only for a small proportion of his engagement time makes this a very inefficient system of stabilization, unless the movements of the gun across its permitted field are rapid. Inaccuracy of stabilization can be counterbalanced by rapid movement of the gun across its swept field, and vice versa; but, other things being equal, inaccuracy in stabilization leads to reduced rate of fire. If we know these physical characteristics of the stabilizer--the proportion of the engagement time for which the gunner considers he is on target, his probability of hitting when he thinks he is on, and the time taken to reload--the effectiveness in terms of likelihood of getting at least one hit can be calculated. The mechanical system can then be designed to optimize this criterion, provided the performances of the two human operators (gunner and loader) are known.

Speed and accuracy with fast moving targets

The most important problems of this class occur in connection with aircraft targets, but significant cases also happen with ships and tanks. Fast moving targets have one limitation in favor of the gunner: they cannot make rapid changes of course. This enables their future position to be predicted if their course and speed at any time are known. Prediction for a target's particular tendency to maneuver will be more or less accurate according to whether the information on which it is based is accurate or not, and more or less useful according to the time elapsing between knowing the enemy's vector, and the arrival of the missile at the projected point.

Consider first a raid on which we have a single radar reading, of average error r feet. The raid is travelling at 300 miles per hour. Delays in the system, due to time taken to set cursors, read scales, and

transmit information to the person who will act on it, total S seconds. In each second the aircraft will travel about 440 feet, so that in S seconds it will travel 440 times S feet. The delay time may easily reach 10 seconds or more, so that the error due to systems delays might easily exceed 4,000 feet. The radar error of r feet is often insignificant compared with this, and any change in the radar which will sacrifice less than 440 feet in accuracy for one second reduction in delay time will be a change for the better. Moreover, the value likely to accrue from any speeding up of the radar reading and communications system is liable to be very great. To estimate this value numerically demands knowledge of the use which will be made of the information. If it is used merely to warn a fleet 100 miles away that an enemy raid is approaching, the delay will not be so serious as if it is used to direct fighter cover to the vicinity.

Take now the case in which the radar is used to provide a vector on the raid, i.e., to plot two or more points on a course so that the future position of the aircraft can be predicted.

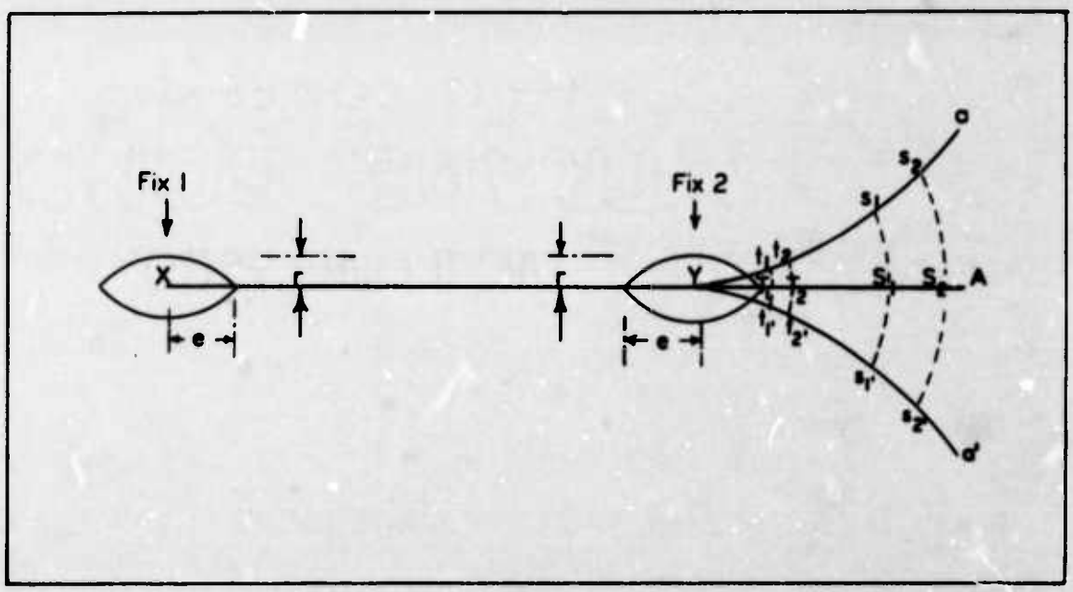

Figure 7. Errors in prediction in antiaircraft fire.

In Figure 7, we show two successive fixes of a raid. Each may be in error by e feet, e being the square root of the sum of the squares of the radar error and error due to delay times. We shall postpone for the present consideration of the exact function of the delay time which must be compounded with the radar error. After the raid has passed through points X and Y, a predictor assumes it will continue in a constant direction at a constant speed to point A. It may, however, change to a new course, Ya or Ya'. Assuming Figure 7 to be a horizontal plot, it may also change height on a course Ya'', not shown on the figure. Differences in delay time in fixes 1 and 2 will lead to a misestimate of speed. If S_1 and S_2 represent the estimates of present position along X-Y-A according to the lower and upper average errors in speed measurements, it will be seen that the raid may be anywhere in a segment of a sphere bounded by s_1, s_2, s'_1, s'_2, s''_1, s''_2, s'''_1, and s'''_2, where s'' and s''' represent bounds in the vertical plane. Suppose S is reduced to a new value T. The ratio of the volume of the first segment of a sphere to the second will be S_2/T_2, if the two segments are of equal thickness and if the courses Ya, Ya', etc., may be assumed straight. Any tendency for the courses Ya, Ya', etc., to continue to curve will increase the ratio.

The distance of S_1S_2 and T_1T_2 are determined by compounding the actual change in speed of the aircraft and the variation in time delay in the system. Long times will usually tend to have larger absolute variance than short ones. The amount of uncertainty as to the predicted position of the raid is, therefore, likely to vary at least as the square of the system delay time (expressed as a distance) and, perhaps, by a larger power. It will, in addition, vary directly as the average variation in the system delay time and as the length of the line X-Y, that is, the time interval separating two successive plots. The accuracy of a radar set may thus turn out to be a very unimportant measure of its operational usefulness: the speed of the communication and radar reading system, the constancy of this speed, and the time between successive readings may be much more significant. The men, in fact, are limiting the performance of the system to a very marked extent. Again, the importance of the errors introduced into the system by time delays of one sort and another can only be judged in terms of the use made of the data: the importance will tend to be much greater if they are used for gun control than if used for CAP control, because the human operators in the CAP may be able to intercept almost equally well with an error of 2,000 feet as with one of 200 feet.

Relationships somewhat similar to this have been worked out by OEG in connection with the attack of submarines by projectiles fired from surface vessels.

CHAPTER IV

GENERAL RULES FOR SYSTEMS ANALYSIS

From the examples given, and the very large number of other examples which could be given, as well as the theoretical considerations given in Chapter I, certain definite rules of procedure seem to emerge.

A. Value

We have seen that the problem of Value will normally involve consideration of the super-system(s) of which ours forms a part. Consider how the function (or Output) of the system is related to its Value. Will small increases in Output be of any Value? Are Output and Value linearly related in the range of Output we shall be considering? How much Cost to us will particular Output have? How much extra Output is wanted? Such problems appeared in many of our examples: we did not need a more accurate sight or a more accurate radar, because they would have made negligible contributions to the Value of the super-system sight-gun or radar-communications network. On the other hand, our airship did need a better system of detecting submarines, because the Output of our super-system depended linearly on detection, which was an inefficient process, and the Output of the super-system had been judged inadequate when compared with the number of enemy submarines and their threat to our shipping.

If Output is directly related to Value over the range with which we must deal, as is fortunately often the case, it is usually possible to quantify Value in this way over small ranges of Output. Then, if increased Output does not appear to increase Value, no further systems research is needed, except perhaps to reduce Cost.

B. Output

Practically every system produces some tangible, physical Output, and to this extent is therefore quantifiable. Systems designed to affect morale lead to difficulties. Weapons systems designed for supporting infantry have a material destruction effect and a morale impairment effect on the enemy; although these two Outputs can be evaluated separately only with the greatest difficulty, if at all, their joint effect

proved measurable in some cases in terms of "cheapness of advance." However, Output measured in concrete, specific, understandable, analyzable terms--such as interception of a raid, destruction of a tank, etc.--is much more useful to the systems analyst than Output measured in such general, all-embracing terms as "cheapness of advance" which cannot, in the present state of our knowledge, be analyzed into their components. Analyzable measures of Output are characteristic of simple systems, low in the system-hierarchy, which produce results which are measurable and analyzable entirely in physical terms. In the present state of knowledge, these are the only systems which are entirely capable of optimization, without continuous experimentation and evaluation throughout operations.

Thus, Output should be measured whenever possible in concrete, specific, entirely physical terms. In general, such measures of Output fall into two groups: probability of succeeding in a particular operation or probable hits on a target, on the one hand; production of so many units of Output, bombs dropped, ships sunk, etc., on the other. These two sorts of measures of Output are treated in the same way in subsequent research, except that there is no upper limit to Output of physical things, whereas probability of success has a maximum value of unity.

C. Analysis of the System

1. Initial Analysis

First of all, Output must be related to Value, so that the rest of the analysis can be carried out in terms of Output. The system which we are concerned to optimize must then be analyzed into its sub-systems of next lower level in order to gain a clear picture of what each of its parts contributes to the whole. An hierarchial analysis is to be preferred, because it enables maximum simplification to be achieved. There will often be a number of ways in which the system may be split up hierarchially. In general, the most functional of the possible methods is to be preferred since it leads to an easier (and more convincing) analysis; however, errors of judgment between two or more possible lines of subdivision will seldom lead to incorrect results.

The relationship between the several sub-systems must now be studied to determine their interdependence, if any. The relationships

may be additive, multiplicative, or a mixture of the two. Certain considerations aid in the appraisal of these interrelationships. If of two sub-systems of the same level, one b follows the other a in time, their performances are unlikely to be independent: the performance of b is likely to depend on the success of a. In this case, the performance of the system containing both a and b will usually be proportional to the probability of success of a multiplied by the probability of success of b.[1] When a system splits into several alternative sub-systems (as the system "destruction of submarines" may split into "destruction by corvette, by destroyer, or by aircraft"), the performances of the sub-systems are generally additive. When performances are additive, special precautions must be taken to account for overhitting. Overhitting is dealt with as follows: Let P be the Output of the whole system, and $P_a \ldots P_n$ be the Output of its various alternative sub-systems, in such a way that P is achieved completely either by P_a, or by P_b, or by P_n, but not by more than one of $P_a \ldots P_n$. Then:

$$P = P_a + P_b (1 - P_a), \text{ etc.}$$

2. Study of Sub-systems of the Second Level

The next step to take depends on the nature of the specific problem. If to the investigator it appears easy to measure the contribution which each sub-system of the second level makes to the performance of the whole system, before taking the analysis down to the next (third) level, it will usually be best to carry out this step. It may be necessary to base this evaluation of the contributions of the various sub-systems of level 2 on specific measurements, on general knowledge, or on judgment. In the case of modifications to existing systems, or the design of new systems along familiar lines, a quantity of statistical information is often available for such evaluation.

It will often be obvious at this stage that one of the sub-systems is in greater need of analysis and improvement than the others. To take a trivial example, if a submarine-hunter is making many contacts

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1 An exception occurs where system b is used after system a has failed. Then the value of a and b will be expressed by an equation containing the term $[P_a + (1 - P_a) P_b]$ where P_a and P_b are the probabilities of success of a and b.

but is seldom making a kill, then it will be necessary to concentrate attention on the killing process, leaving contacting to take care of itself. To take a slightly more complex example: suppose in the case of the submarine-hunting airship (example in Chapter III, p. 28), the proportion of time spent over the target area is a large proportion of total time, analysis should be directed at what the airship does when it is over the target area. If time over target is a small proportion of total time, one would examine it to see if it could be greatly increased before attempting to improve efficiency while over the target area.

One advantage of evaluation at each level of the hierarchy as it is reached in the analysis is that it gives a series of priorities and permits attention to be concentrated on the most crucial parts of the system. This advantage might be bought at too high a price if evaluation at a particular level demanded more effort than analysis and evaluation at the next lower level: a question which the systems researcher will always have to handle on the basis of his judgment and experience.

It should be noticed that the level-by-level analysis will only indicate the increase in Value likely to be obtained by improvement of particular sub-systems, not the Cost of attaining the Value. The Cost must, of course, be considered. However, its estimation is not usually considered to be a part of systems analysis; instead, it is usually estimated with adequate reliability by engineers in the appropriate field. The sub-system showing likelihood of biggest improvement in the criterion should be given priority for further study; this will usually be the sub-system showing the biggest room for increase in Output.

3. Study of Sub-systems of Lower Levels

The sub-system of the second level which turned out to be the least adequate should now be analyzed as in Step 1 above, and its parts evaluated as in Step 2. If no one sub-system turned out, as a result of Step 2, to be of higher priority than the rest, all would require study. This would also be the case if evaluation at the second level was judged by the systems researcher to be too difficult to be worth doing. Still lower levels should be analyzed in like manner, the analysis continuing until it is clear how improvement can be made in the most crucial sub-systems.

4. Re-evaluation of the Whole System

The new performance of the system, taking into account the improvement made in Step 3, must now be measured or estimated, and its adequacy evaluated. If still inadequate, attention should next be focussed on the sub-systems which the analysis has shown to be of the next highest priority.

D. The Cost of Improvements

The Cost of each improvement suggested by the analysis at any stage must be evaluated by someone before a sound decision can be taken as to whether or not to make the change.

If the systems researcher is not to make this evaluation himself, he should obtain some early guidance from the Cost assessor as to what sort of improvements are likely to be cheap, and what sort dear. Cheap and dear are relative terms: they can only be reasonably employed in connection with Costs demanded by other systems, and with the Cost to us of not making the improvement. Costs demanded by other systems cannot generally be rigidly compared with the Values of these other systems, because the number of systems is too great, and measurement of their Value too complicated. In practice this situation results in policy judgments as to whether the organization concerned can or cannot afford certain Costs. The Cost of not making the improvement is somewhat more susceptible of quantification. (An example was given, p. 34, of the Cost of not attacking a bomber.) The Cost to us of not destroying an enemy submarine can be equated to the damage (in terms of lost ships and cargoes, time delays due to use of the convoy system, and so on) likely to be caused to us by the submarine if it survives. For small changes in rate of destruction of submarines, this is measurable statistically in terms of ships and cargoes lost, and longer voyage time, divided by the average number of enemy submarines which caused this damage. The monthly loss to us in this form is then multiplied by the average life, in months, of a submarine with present systems of ASW, to give the Cost to us of each submarine not destroyed.

E. Investment Required to Produce Improvements

The Investment required to produce improvements should also be considered, along the same lines as Cost. The use of the airship

in antisubmarine warfare will now be worked through in considerable detail to illustrate further the necessary steps.

Level 1. Systems for destruction of submarines. Do more submarines need to be destroyed? Policy decision is that they do. Can more submarines be destroyed? Many submarines, though within reach of our forces, survive for long periods. Clearly, increasing the number of submarine-hunting weapons would increase destruction, and increased efficiency of individual weapons may be possible.

Decision: Analyze the problem further, using the criterion "submarines destroyed per unit cost."

Level 2. The following systems exist: destroyers, corvettes, airships. Information is that ASW airships are a comparatively new and hence probably a relatively underdeveloped weapon. They have had, nevertheless, considerable success in the past. No major improvements in ASW by destroyers or corvettes can be foreseen.

Decision: Analyze further the airship ASW system.

Level 3. Effectiveness of the airship ASW operation will depend on: a, number of airship hours spent over areas where submarines are operating; b, number of submarines destroyed per airship hour over the area. Effectiveness will be the product of a and b. It is not possible to say at this stage whether a or b will be the more easily improved by the larger factor.

Decision: Analyze further both a and b.

Level 4. Airship hours over submarines' operating area is controlled by n, the number of airships, and f, the fraction of their lives spent in operational flight. To double n would probably result in doubling or almost doubling the number of kills, since there appears to be no likelihood of the airships running short of targets. But doubling n is an expensive operation, and cheaper ways of increasing the number of kills should be sought; f is, therefore, evaluated. If it is considerably less than figures found in comparable organizations, measures should be taken to increase it. If it is about normal, it is unlikely to be susceptible to much improvement. If its absolute value is high (0.5 or more), only minor increases in number of kills are

likely to result from study of f. On the other hand, improvement in f would be likely to be inexpensive.

Decision: Reserve n for later study if it turns out to be the only possible means of obtaining the required improvement. Study f further.

The probability of destroying any particular submarine in the area will be the product of the following fractions:

A - Proportion of whole area under surveillance by any one airship at any one time.

D - Probability of detecting a submarine in A.

L - Probability of locating successfully any submarine detected.

T - Probability of gaining position for an attack on any submarine successfully located.

K - Probability of killing any submarine attacked.

Research on, and maximization of, all these five processes would be slow and expensive. We must, therefore, set up a priority among them. Existing operational information, canvassing of experienced personnel, and in-the-field study of the operation show (let us suppose) that the following are reasonable estimates of these fractions: A = 0.05, D = 0.10, L = 0.95, T = 0.90, K = 0.25.

Decision: Concentrate on the smallest first; that is, attempt to maximize A.

Level 5. Analysis at Level 4 indicated that f, fraction of time spent in operational flight, should be studied further. Study of operations at several airship bases shows no likelihood that f can be improved significantly. On the other hand, not all of f is spent in destruction of submarines: time is spent getting to and from the base and hunting grounds. Increases in endurance of the airship could increase the effectiveness of the hours flown; so could reduction of distance between base and hunting area. The latter turns out to be impossible. Increases in endurance are only possible by reducing the

weight of equipment or crew carried. Only 10 percent of time over target is lost (let us suppose) in flying from and returning to base.

Decision: No further work on f would be justified.

Analysis at Level 4 also indicated that the least adequate sub-systems involved in destroying a particular submarine should be maximized.

Decision: Maximize A, D and K (in that order), using the procedure which has already been given in fair detail.

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CHAPTER V

HUMAN ENGINEERING IN SYSTEMS RESEARCH

This study has covered so far a discussion of the meaning and some of the history of systems research, a theoretical study of the most difficult problem therein--that of criteria--and a set of examples typifying some of the ways which experience has shown to be useful in the analysis of systems. The work done on systems up to this point will show where efforts at improvement will be most effective and how military specifications may be reached scientifically; it will end up with specific recommendations such as "improve the round-to-round accuracy of the gun" or "provide a rangefinder" or "decrease time spent in reloading" or "increase the range of detection of the radar."

No attempt has yet been made to show how the various desirable changes can be accomplished. In so far as the techniques used for their accomplishment are parts of well recognized and fairly well-known academic disciplines, any detailed discussion of them would be out of place in this report: the systems analyst can consult suitable text books. There are, however, two fields of knowledge which are either inadequately covered in available texts or are so poorly understood by many people who could make good use of them that they deserve special mention. The first is human engineering, the second probability and statistical methods. Both are of very great importance in systems research: the former because no system yet conceived is independent of human operators; the latter because this dependence on human operators, as well as the uncertainties of war, demands that we think in terms of probabilities and not in terms of clear-cut black and white certainties.

A. The Importance of General Principles and Data of General Application

Most engineers nowadays pay some attention to a number of ways in which the machine can be designed to fit the man, but few or none pay enough. Probably basic human dimensions and sensory acuities are the two fields most often considered by designers of mechanical, electronic and optical equipment. This is perhaps because most information of general application is available in these fields. It is easy to find out from published tables how big men are, and there are good average figures

[redacted]

for their sensory acuities in various conditions. Much less information is available on the effects on performance of environment and morale, on power of concentration, and on means of selecting the rare individuals possessing the necessary abilities to work some complex machine; and the existing data are usually less general in application and more difficult to interpret. As a result, the first two fields are generally paid reasonably adequate attention in original design, while the remainder, attention to which often demands ad hoc research, will often be ignored altogether or added in a rather makeshift manner, at great expense, when the machine is in production.

Even if insufficient attention is paid in original design to the well-known general principles of human engineering, the equipment can often be modified at a late stage at small cost provided: 1) no ad hoc research is required, and 2) the designer has left enough space for the operator to get comfortable and to move about. The following factors can usually be brought near to their optima without either expensive research, or expensive redesign or interruption of production: lighting; seating; positioning of displays; logical arrangement of controls; size, travel, plane and gear ratio of controls; touch coding; design and organization of instrument dials; noise; communications; visibility; and warmth comfort in so far as this can be achieved without large heavy current-consuming fans. A good deal of general information exists on all of these, and they usually involve small or movable installations which are cheap. Therefore, we need not trouble to assess their Value before installing them. The problems of optimizing these factors will tend to become progressively easier as more and more reliance is placed on electrical (or hydraulic) links and less on inflexible mechanical ones.

We see then that systems can be improved from the human engineering point of view by the following means, among others:

1. Increasing the body of general knowledge of human engineering facts, figures and principles.

2. Spreading this knowledge among mechanical, hydraulic, electrical and optical engineers.

3. Giving new systems flexibility in arrangement of controls and displays, and leaving space and power sufficient to allow rearrangements of men and equipment in the light of experience and expert knowledge of men.

B. Spurious General Principles

The human being is so complex, and will operate under such a wide variety of environmental and psychological conditions, that principles which appear applicable may be very misleading. One simple case is in laying a telescope reticle on a target. A number of investigations have shown that soldiers making careful lays on targets with non-magnifying observing instruments will make errors as big as two minutes; yet the acuity of the average eye is such that an error of about a tenth of a minute can be detected. From this it may be deduced that some other factor is controlling the accuracy of the man's performance. If we make the experiment of increasing the magnification of the telescope, we find that accuracy also increases, although not quite in proportion to magnification. The controlling factor, therefore, is not the man's muscular ability or the smoothness of the mechanical controls. It is believed to be the man's idea of what he ought to do. He makes a smaller error when using a bigger magnification because his error, which he saw perfectly well before, now looks more unacceptable. This idea receives confirmation from a paper by Helson[1] in which the simple process of magnifying a tracking error between two pointers caused the operator to reduce his error, though it was perfectly visible to him throughout the experiment. Moreover, if an amateur and an expert surveyor both make a series of lays on a target with a theodolite, the amateur will generally make more variable lays than the expert: not because his eyes are less acute, or his fingers more clumsy, but because he sets himself a lower standard of what he means by "right."

Another example might be drawn from studies of warmth comfort. A long series of studies of what people regard as comfortable when working in large buildings without temperature gradients have led to standards of effective and equivalent temperature. Other scales have also been used (eupatheoscope, globe thermometer). But these results do not apply at all accurately to circumstances where pronounced temperature gradients exist either vertically or horizontally. Nor do they apply when the air and the radiating or radiation-accepting surfaces are at very different temperatures. Such conditions are common aboard ship.

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1 HELSON, H. Design of equipment and optimal human operation. Amer. J. Psychol., 1949, 62, 473-497.

Great care must thus be taken in human engineering that the general principles apply in the specific case.

C. General Studies Needed

A great deal of valuable information could be obtained in the following fields and applied to systems research:

1. Conditions under which machines should replace men and vice versa
2. Display of complex information
3. Transfer of training
4. Performance of radar operators
5. Attention
6. Selection of men of optimum size
7. Acceptance of errors
8. Effects of comfort on output and incidence of mistakes
9. Fundamental study of tracking response
10. Rate at which new data can be assimilated

The rest of this chapter is devoted to brief discussions of each of the fields listed above.

1. Conditions Under Which Machines Should Replace Men and Vice Versa

Paul M. Fitts and nine distinguished collaborators in a study of air traffic control systems conclude that men surpass present day machines in flexibility and the ability to:

Detect energy of certain wavelengths

Perceive patterns and generalize about them

Improvise and use flexible procedures

Store facts for long periods and remember them when needed

Reason inductively

Exercise judgment

whereas present machines surpass men in

Detection of wave lengths to which man is insensitive

Quick response to control signals

Smooth and precise application of force

Performance of routine repetitive tasks

Storage of information for brief periods and its subsequent complete erasure

Deductive reasoning and computational ability

Ability to handle highly complex situations, i.e., to do several different things at once

Men are on the whole poor monitors, due to wandering of attention.[1]

These, of course, are all qualitative statements. Since men and machines have very different costs, quantitative statements on these matters are needed if systems are to be optimized without continuous specific ad hoc research after they have been built. They form, however, a useful guide to present action.

2. Display of Complex Data

The job of the man in a modern military system is generally to respond (by movements, orders or statements) to information which he acquires in one of three ways: direct perception of the situation to

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1 FITTS, P. M. (Ed.) Human engineering for an effective air-navigation air traffic-control system. The Ohio State University Research Foundation, Columbus, Ohio, December 1950.

which he must respond, information presented to him by another man, information presented to him by an instrument. We will not deal here with information the man obtains through direct perception of the situation. Moreover, we shall confine the category "information presented to him by another man" to verbal and written messages; information plotted on a display board will be regarded as an instrument presentation.

Verbal and written messages

Provided the impact on the man of the messages to which he is subjected does not tax his powers of hearing, vision and assimilation severely, the main problem is to avoid mistakes in transmission. This can be done by:

Good electrical and acoustic design of circuits

Reduction of background noise

Keeping the number of linkages to a minimum

Training in good enunciation

Development of standard format for messages

Prevention of distractions

Design of telephone jacks, head harness, etc., to allow the man to be comfortable for long periods, to move about as freely as possible, and to find the jack easily and quickly again after disconnection

It is often desirable, for a man who may have to make decisions for himself in emergencies, to allow one ear to remain free so that he can keep himself informed by a kind of automatic eavesdropping on the general situation of other sub-systems with which he may become concerned.

When it becomes apparent that a man's powers of perception and assimilation are liable to be overtaxed during some phases of operation, two possible solutions present themselves: if the problem is one of perception, use more than one sense (for example, sight as well

as hearing); if the problem is one of assimilation, ration the input of messages, to those which are most important. In the case of verbal and written messages, power to perceive is seldom overtaxed; power to assimilate often is. Examples are likely to be found in such tasks as those of the Air Control Officer, who has to keep track of the evolutions and importance of several enemy raids at the same time, or of the pilot who has to change over rapidly from instrumental to visual flying or vice versa. An information rationing system has to be based on some scale of the relative importances of the various sorts of information available. This may be obtained from a logical analysis of the man's place in the system, a questionnaire addressed to those with experience in operating the same or a similar system, or a field study of what a sample of men in that position actually use. Preferably, the scale should be based on all three sources of information, since none by itself is adequate. The information of the highest priority is then to be pumped into the man's ear, or put in front of his eyes, while the rest may be kept from his attention altogether and acted upon at a lower level of the system, or displayed on some board, plot or chart which the man can refer to if he wishes and has time.

Instrumental displays

Displays may be classified as symbolic and pictorial. A display may be called pictorial if its geometry conforms to that of the information being displayed. An air photo, a map, an image seen through a telescope, or a PPI presentation on a radar are pictorial in this sense. An instrument dial or an engine annunciator are symbolic. Many displays have both symbolic and pictorial characteristics. The nature of the information may necessitate a symbolic display: there are many things of which meaningful pictures cannot be made, such as temperatures, pressures, etc. These are normally displayed as dial readings.

A great deal of information exists on the proper design of dials and the letters or numbers associated with them. Before choosing the dial, certain questions have to be answered:

(1) Is the instrument a single unit or functionally associated with other units?

(2) Is it to give a "yes or no" answer (e.g., oil pressure high enough or not), or a static "how much?" answer (what is the depth of the submarine?), or a dynamic answer of "how much, how rapidly changing, in what direction"?

(3) Will the dial be showing slow or rapid changes?

(4) How accurate must it be?

(5) Who will use it, in what conditions, from how far away?

Instruments which give a yes or no answer can often be advantageously replaced by tell-tale lights which change, say, from green to red when danger approaches. These have the merit of drawing immediate attention to an emergency, and their use will generally increase the power of a single individual to monitor a number of installations. The lights may be combined with a buzzer, which indicates "something wrong" while the light indicates with minimum delay what is wrong. To minimize the effects of bad memory or poor training, the indicators should be arranged as logically as possible according to their spatial or functional relationships to the machines to which they refer. Circular-dial instruments are generally best, and their scale reading should increase in a clockwise direction unless there are very good reasons for the contrary. The dial should contain no more detail than will be used, and consequently should be so arranged that a reading to the nearest scale division will be of the most economic accuracy. Divisions should be clearly numbered, but the dial not "cluttered" with numbers; divisions should be on the decimal system, of equal value throughout. The meter should be labelled with its function and the units it measures. Numbers should be printed horizontally, and the pointer should not obscure them. Cover glasses should not cause glare: hence one of the merits of edge or background lighting.

Long scales needing accurate reading are often best designed as open window instruments, in which a single figure with another either side appears in a window. These are bad, however, in two situations: rapid change in which the numbers pass the window too fast to be read, and the converse problem of setting the dial to read a particular figure. When "rate of change" is important to the man, a special rate-of-change instrument should be provided.

Instruments may have to give the information "yes or no" on one occasion, and "how much" on another. The best solution to this problem is often to use pointer and dial type instruments, arranged close together in a logical order, with all the pointers parallel in their "normal" position. The normal position should preferably be vertical (12 o'clock) but may be nine o'clock.

To insure that instruments are read as easily and quickly as possible, with a minimum possibility of gross error, they should be made to display only as much accuracy as the operator needs. This will also give the operator a standard of the accuracy required from him: thus, less accurate instruments may produce more accurate readings. It goes without saying that all instruments should always be easily read by the man who has to use them from his normal station. Precise information now exists on the optimum size and shape of numerals and letters.

Pictorial displays

There is very little information of general applicability on pictorial displays. However, this type of display is normally to be preferred when the nature of the information to be transmitted makes it possible. It requires less training, is easier and quicker to interpret, and emergency responses to it are less liable to be faulty. To be pictorial, the display need not contain all the features of the original: only those to which the man ought to react, together with enough background to be readily intelligible. Charts and PPI scopes are examples. Nor is it necessary that the scales in the three geometrical planes be undistorted: for example, they have to be distorted in relief maps for the relief to be noticeable.

There are many displays which combine pictorial and symbolic features: examples are contour maps, where height is displayed symbolically (typically it is found that the height component is the most difficult to teach, read and interpret), and the Air Plotting Board, which has to represent a four-dimensional situation, since it must include time and often speed, on a two-dimensional plot. Research on the errors and mistakes made in using radar scopes, plotting boards and charts of various types would be of great value, and might result in such standard rules as have been summarized above for instruments of the dial type. Such studies should deal with both static and dynamic situations, and with both deliberate and at-a-glance use by the operator.

Direction-of-motion displays

Should a Landing Control Officer on an aircraft carrier hold his flags up or down to indicate to the incoming pilot that he is too high and must come lower? Problems similar to this arise fairly frequently, and there appears to be no general answer. The direction of movement should

be "natural," but we often have no means of knowing to what aspect of his normal existence the man will relate the display situation unless we do specific experiments. These are often difficult: for example, we cannot do experiments on piloting aircraft without using subjects who already have some degree of training, which may have altered their conception of what is natural. The only general statement possible seems to be that the designer should strive for consistency: once a system has been designed and used by a large number of people, it should not be changed in direction without very strong reasons.

3. Transfer of Training

One of the areas in which present systems pay least effective regard to the limitations and peculiarities of the men who operate them is probably the useful or disadvantageous transfer of training. The problem arises in the following areas among others: position of controls and displays, gear ratio of controls, load of controls, plane of controls, marking of instrumental displays, sequence of operations, methods of tuning, zeroing and adjustment equipment, maintenance of equipment, operating rules of the "keep to the right" variety, form of reticles in optical instruments, standard procedures in voice and flag transmission. No quantitative guidance of any sort is at present available. There are only general qualitative principles:

(1) Complete semi-automatic sensory-motor training is attained very slowly: once attained, therefore, it should not be wasted, but transferred over as completely as possible to the new equipment.

(2) Once attained, it is very firmly fixed in the individual. If new equipment demands movements in different directions or in a different sequence, training on it will be slow and frustrating.

(3) When training on the new equipment has apparently become practically complete, fatigue, stress or emergency may be found to produce reversion to the mode of action appropriate to the old equipment, sometimes with disastrous results.

Research should be aimed at determining quantitative statements as to how much retraining is necessary in various conditions, and what this

costs in delays and man-hours; research should also be directed at finding ways (for example, by changing the gestalt) by which the adverse effects of carry-over of the old techniques to an inappropriate situation can be minimized.

4. Performance of Radar Operators

The "designed" maximum range of detection of a radar will be reduced in practice by several factors. The first is imperfect maintenance, which is often impossible to avoid in service conditions. The second is inadequate tuning procedures. These two factors prevent faint blips appearing at extreme ranges; and of course if no blip appears on the screen, the operator, however good he is, will fail to detect the target. Probably, however, a more important practical limitation to performance arises from the fact that the man does not scan his screen in a perfect manner. Unless he is well motivated or well supervised, he may have his eyes closed or be looking at something else, or he may be day-dreaming for a large or small fraction of the time he is supposed to be searching for targets. The extent to which this actually happens in war is not known, but it may be presumed that it can be reduced by improvement in morale, rotation of duty, prevention of distractions of all kinds, and by making the general environment comfortable but not soporific. Insertion of a test blip might also be useful. While he is actually looking at the screen and paying full attention to it, he may give one sector of it predominant attention. Unless there is reason to suppose that the sector to which he gives most attention is the region where the likelihood is greatest that targets with a high product of frequency and importance will appear, such selectivity will reduce his overall performance. If his eyes attempt to follow the sweep line round the screen, the large proportion of the time that his eyes are moving may militate against his likelihood of seeing a fresh target. It seems likely from the literature that such "human factors" reduce the likelihood of seeing new targets to about one-fifth of what it would be with a theoretically perfect operator; it therefore follows that research directed systematically to produce optimum rates of operator rotation, good working conditions, better scanning methods and so on, would be capable of producing results of great practical importance, increasing the value of all present and future search radars by a large factor. Such research might also suggest methods in which the nature of the display could be changed to make performance less dependent on the vagaries of man. Ways in

which it is conceivable that this could be done have already been presented in this report (see p. 69).

If the probability of an individual operator seeing a particular new blip is small, there is a theoretical likelihood that addition of extra operators would greatly increase the probability of seeing targets. The maximum improvement to be expected will be determined by the following relationships:

One operator: P_o

Two operators: $P_o + P_o(1 - P_o) = 2P_o - P_o^2 = P_2$

Three operators: $P_2 + P_o(1 - P_2) = P_3$

where P_o is the probability of any one operator seeing the new blip. If P_o is large, the effect of adding new operators is small. It is also small if each operator tends to see the same blips and to miss the same blips; this would happen, for example, if all the operators were talking to one another. This may be called, loosely, correlation between operators. The extent to which it occurs is unknown, and so the extent of improvement of performance attainable by addition of extra operators is not at present predictable. It is highly important that such experiments be carried out, for an extra man, or an extra repeater-scope for use by men temporarily unemployed, is usually far cheaper than development and production of a radar set of twice the range. Work done on sonar gear, although not precisely comparable, has suggested that though the maximum theoretical effect of additional operators is not achieved, a worthwhile improvement nevertheless results from increasing the number of operators.[1]

Human problems are also important in connection with use of radar to give vectors for use in defense against enemy aircraft. It was shown in this report (see p. 32) that time delays in the use of radar data for this purpose, and variation in time delays, tended to be much more important than the accuracy. A number of studies on the subject exist but, so far as it is known, human engineering methods have not yet been applied to increasing the constancy of time delays,

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[1] SCHAFFER, J. H. Detection of a signal by several observers. USN Electronic Laboratory Report No. 101, San Diego, Calif., 26 Jan. 1949.

thus permitting them to be zeroed out in operating procedures. This is potentially an important field for research: just as in line production it is important to gear the speed of the assembly line to a rate at which most men can work rather than to the performance of a "stakhanovite."

5. Attention

Almost everyone is subjectively aware of the tendency for attention to wander during the performance of monotonous or rather inactive tasks. Jobs of this nature form one field in which the machine can with advantage replace the man, for machines are permanently attentive. There are, however, many cases where this is quite impossible with our present knowledge. Scanning for targets, either visually or instrumentally, is probably the most important of these. Studies on the decay of attention as a function of time, and how attention may be increased by control of environmental and morale factors, appear to have great potential value. They could lead, among other things, to the development of optimum periods of rotation of duty, which would have Value but practically zero Cost.

6. Selection of Men of Optimum Size

This is a very simple, obvious and, at first glance, uninteresting field of study, from which useful results might well flow. So far it appears to have been completely neglected. Two examples of its possible application will be given.

The first is the anti-submarine airship. The Value of this system depends, to a degree determined by the geographic relationships of the base and the operations area, on the flight endurance of the aircraft. Suppose it has a crew of 10 men, whose present average weight is 180 pounds. If their average weight were reduced to 140 pounds, another 400 pounds of fuel could be carried. The saving in weight would actually be even greater, because the cabin could be smaller, stocks of food and drink lighter and so on. Four hundred pounds of fuel is equivalent to about 80 gallons, all of which could be spent over the operations area.

The second is the tank. The internal volume of a tank is divided between men, automotive equipment, and armament very roughly in the

ratio 4: 4: 2; and its weight between armor, automotive equipment and armament is divided in somewhat similar proportions. The height of the turret is determined by the height of the men in it. If this height is reduced six inches by selection, the volume of armor saved will be about .5 x 6 x 3.14 x 0.70 cubic feet with a six foot diameter turret and eight inch armor. This is about six cubic feet or 3/4 ton. Concomitant reduction in leg-length of the driver would save a transverse band of armor in front of the turret about three inches long, and of volume .25 x perimeter of tank x the thickness of the armor, which we may take as about six inches. This is about four cubic feet, or about half a ton of armor plate. This total reduction in weight of armor of the order of 1.25 tons will lead to reduction in weight of the automotive equipment and the armor surrounding it, and give a considerably cheaper tank, offering a smaller target to enemy fire with no reduction in performance. A tank production program of 35,000 a year would save, if this reduction in size proved feasible, between 35,000 and 50,000 tons of armor plate a year.

7. Acceptance of Errors

Acceptance by the human operator of errors is a topic of wide application in military operations which frequently involve some kind of "pointer-matching" action by the man. This type of action is found in such diverse operations as tracking an aircraft, reading a map, measuring range and bearing with a radar, setting a range drum, laying a telescope and using a range-finder. It has two major consequences: 1) there is no point to providing equipment which will give much greater accuracy than the man will use; 2) training and selection are often capable of improving considerably the operational performance with present equipment.

Study should be made of ways in which a man's tolerance to his errors may be reduced. Possible lines of attack are: provision of a magnified display, an increase in the number of scale divisions (or provision of a "clicker" gear), selection, and training. Magnification of the display seems usually to be effective, but is sometimes not feasible. For example, with optical instruments it is accompanied by reduction of field of view; and if the exit pupil of the instrument is to remain high enough to avoid problems in dim light and eye centering, magnification also involves a proportional increase in size of the instrument. Results noted in the work of Dunlap and Associates, Inc., on

the problem of human errors in predicted artillery fire suggest, although they are insufficient to prove, that the tolerance of the human operator to error is closely related to the size of a scale division. This deserves further study. Many studies on the accuracy of coincidence rangefinders suggest that the population of army rangetakers is highly variable in its tolerance to error, and that selection of the best 10 percent of men would be equivalent to doubling the length of the instrument.[1] It seems likely to be the cheaper solution. Incidentally, British World War II studies of German rangefinders revealed that their significantly greater accuracy was probably to be ascribed to their larger, smoother, easier controls, which were free from backlash.[2]

8. Effects of Comfort on Output and Incidence of Mistakes

The physical factors and their interrelationships necessary to provide comfortable conditions in apartments and factories are now well known. The limiting factors as regards wet-bulb temperature are also known for various kinds of work, but the effects on performance of the intermediate ranges have so far been only a little studied. Mackworth gives figures for the effect of wet-bulb temperature on the frequency with which Morse-code operators make mistakes, and shows that no serious deterioration occurs until wet-bulb temperatures reach the high eighties.[3] In the nineties, very serious increases occur. Head colds also were found to have a considerable effect. There is a good deal of evidence that certain specific wave lengths of heat radiation have bad effects in closing the nasal passages, which would

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[1] See British Fighting Vehicle Design Establishment and Army Operations Research Group reports.

[2] See British Tank Armament Research reports of 1944-45.

[3] MACKWORTH, N. H. Researches on the measurement of human performance. Medical Research Council Special Report Series No. 268. London: HM Stationery Office, 1950.

be expected to have effects of the same type as head colds. This evidence is summarized by Yarnold.[1] Stuffiness of this kind, which is more common perhaps than very high wet-bulb temperatures, may have effects on performance of tasks demanding accuracy, attention and clear thinking, and should be investigated. Radiation may generally be easily prevented by use of polished metal, aluminum foil, or some metallic paints on hot surfaces.

9. Fundamental Study of Tracking Response

Many ad hoc studies have been made of the tracking performance of men using various kinds of power operated gear, as well as manual power applied via rack and pinion gearing. They have led to the view that some sort of control handle operating a servo mechanism is more effective for tracking than manual methods, though the latter are better for laying on stationary targets. A roughly logarithmic control characteristic is also desirable. The control should be "stiff"; that is, there should be a minimum time lag between the control being set to a new speed, and the object (gun, etc.) being controlled attaining the same speed.

Some devices, such as gyroscopic sights, depend for part of their input on the movement of the gun, etc., controlled by the operator, so that they tend to be sensitive to the pattern as well as to the error with which he tracks. Little is known about such tracking patterns.

Fundamental work which has been done on manual tracking might with advantage be extended to servo tracking.

10. Rate At Which New Data Can Be Assimilated

It is known in general terms that it takes a finite time, which may be long, for a man to study a situation displayed to him and to appreciate it sufficiently for him to reach a logical conclusion on his most appropriate action. There is no information on how long it takes men of different capacities to assimilate various kinds of displayed information. In many systems, the efficiency is sensitive to the nature of the decision reached and the time taken to reach it; and the

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[1] YARNOLD, K. W. Factors affecting warmth comfort and stuffiness in domestic rooms. J. Hygiene, 1947, 45 (4), 434-442.

consequences of bad decisions or undue delays in reaching good decisions can be evaluated. In systems of this kind, optimization may demand that the information presented to the man should be rationed, and this must be done on a basis of priority. Such rationing may in turn demand that equipment be modified and/or that certain decisions should be relegated to a lower level. At present, there is no sound basis on which this can be done without ad hoc experimentation on the completed system in operation, always an expensive procedure in terms of research, retraining and redesign.

DUPLICATE

O. Bailey
August 11, 1950

LINKAGE CHARTS AND DIAGRAMS

We have used linkage charts and diagrams in the past to illustrate the relationships between personnel and machinery in equipment arrangement problems as a supplementary, sales and presentation feature. The use of these charts for presentation purposes alone makes their construction, which is sometimes very difficult, worthwhile.

Experience in constructing information flow charts and man-machine linkage diagrams has shown that they can be valuable techniques in the "core study" of abstract relationships. Instead of drawing up the graphic form after a project is completed, they should be attacked immediately after orientation. This proposition is based on the belief that once a person is able to set down these relationships in a form which by its limitations defines them, that person has solved his problem.

A linkage chart is a definite contribution to a systems analysis in making possible the ready visualization of the relationships of one unit of a system to the whole. It should be pointed out that this graphic form presents, in content, nothing which could not be verbalized. The advantage lies in the simplification of complex and mentally unwieldy systems by previous definition.

This previous definition is accomplished by setting up codes for the various aspects of man-machine relationships. Linkages can be thought of as tasks performed, information communicated, etc.

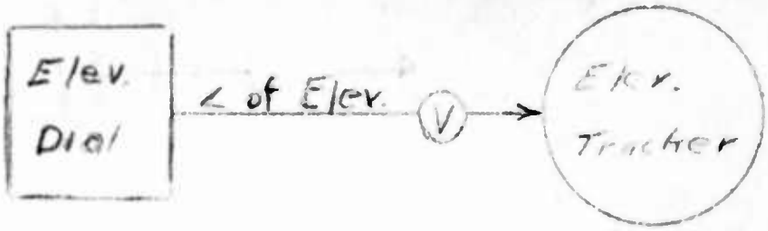
Linkages have direction:

1) Transmitting or originating from
2) Receiving or operated upon
3) Interacting (in the final analysis this can be broken down into fine elements of 1 and 2, but this may not be convenient, possible, or useful)

Linkages can be classified sensorially:

1) Auditory-oral
2) Manual; tactile, kinesthetic
3) Visual
4) Combinations of manual, visual, oral

Linkages have content in the sense that they may be work performed or messages communicated. Linkages may be easily codified as to direction and sense, but not content. Below is an example of codes and symbols used on information flow charts.



The square representing the machine and the circle representing the man are the terminal points of a visual linkage. The combination of the three elements composes a simple system (the most elementary system). Complex systems are composed of several simple systems which are in some way related. These symbols and codes are much easier to manipulate than are sentences, paragraphs or pages, which might be required to define this relationship.

One specific application of this diagrammatic analysis is in the comparison of the degree to which the "chain of command" in a system coincides with relations which arise along the flow of work. This can be accomplished by constructing two charts showing the same individuals and pieces of machinery, one illustrating the sociological relationships of the group, the other showing the assigned organizational responsibilities.

Other applications are the study of:

1) the transmissibility of emotional tensions created by job content, and
2) the efficiency of communication within psychophysical systems.

It must be realized that symbols and codes impose limitations sometimes to a greater extent than they clarify. In long run basic research problems, the necessity for definition within fairly precise limits may prevent the discovery of new aspects. However, for a complex short run problem, linkage charts can be utilized to great advantage in the study of abstract relationships.