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DESIGN OF A STATUS MONITOR USING COST-EFFECTIVENESS ANALYSIS

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DESIGN OF A STATUS MONITOR USING COST-EFFECTIVENESS ANALYSIS

By
Philip B. Pease

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

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FOREWORD

This document attempts to illustrate the application of cost-effectiveness analysis as a practical tool for the systems designer. In particular, a method for selecting which parameters should be monitored in order to assess the operational status of a telemetry system is illustrated.

A paper, "Cost-Effectiveness Analysis: An Appreciation," by E. S. Quade of the Rand Corporation is presented as an appendix to this document. As the primary purpose of this document is to illustrate the use of cost-effectiveness analysis, it is recommended that this appendix be read prior to reading the main document.

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DESIGN OF A STATUS MONITOR
USING COST-EFFECTIVENESS ANALYSIS

1. INTRODUCTION

Figure 1 shows the general design technique used to design a status monitor* for a satellite ground station. This document will describe in detail how each step of the design technique was accomplished to produce the design of a status monitor for the telemetry portion of a ground station.

The telemetry installation considered in this document was proposed for the new Network Test and Training Facility (NTTF) located at the Goddard Space Flight Center in Greenbelt, Maryland. Figure 2 is the basic functional diagram of this installation.

2. THE STATUS MONITOR DESIGN

The primary function which must be performed when designing a status monitor is to make a decision as to which, of all the possible parameters that could be monitored, should be monitored. The basis for making this selection is to determine which parameters are the most effective in assessing the status of the telemetry installation and are the least costly to monitor.

The effectiveness of assessing the status and the cost to do so are, in general, opposing factors. The selection thus becomes one of determining the monitoring configuration which exhibits the best effectiveness to cost ratio (effectiveness/cost).

This section of the document will describe how each step of the design was accomplished in order to determine the optimum status monitor.

2.1 Step 1 - Define the Objective of the Status Monitor

This step is the most important step in the design process. Designing a system which meets the wrong objectives is like solving the wrong problem. The resulting design may be completely inadequate or, as a minimum, a suboptimum design will result. The most frequent error is selecting objectives which are too narrow in scope.

*The term "status monitor" as used in this paper refers to the tests to be made in order to assess the operational ability of the station and the hardware used to implement the tests.

(1) Define the objectives of the Status Monitor.

(2) Describe the operational requirements of the ground station.

(3) Specify measurable quantities which most directly represent the operational requirements (these quantities will be called "performance indicators").

(4) Develop methods of measuring the performance indicators and, as an alternate, parameters related to the performance indicators.

(5) Specify measures of effectiveness and cost to be used in rating the methods of measuring the performance indicators and their alternates.

(6) Screen the alternatives to determine the monitoring configuration with the greatest effectiveness/cost rating.

Figure 1. A General Design Technique for a Satellite Ground Station Status Monitor

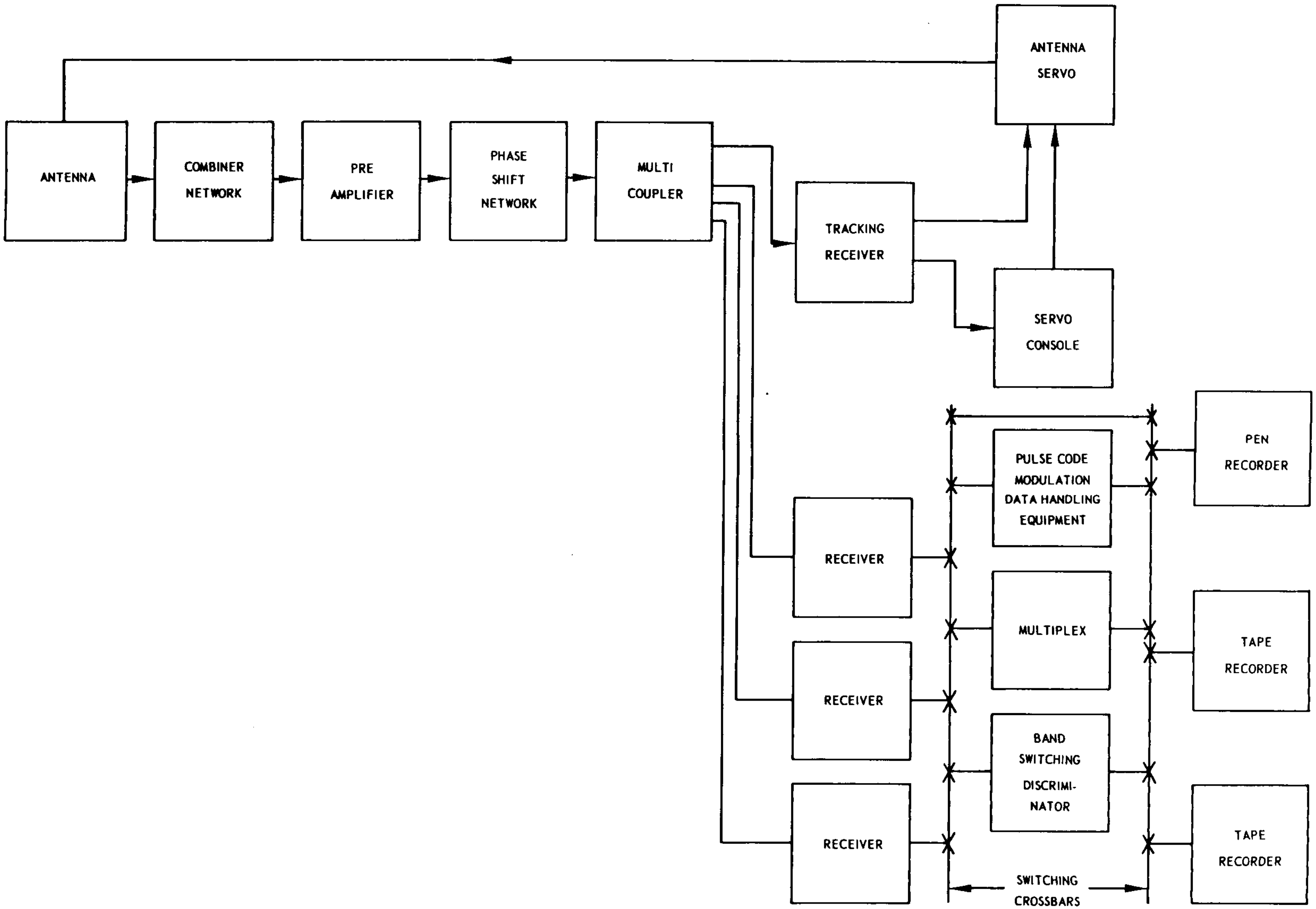


Figure 2. GSFC Telemetry Basic Functional Layout

The objective of monitoring the status of a ground station is to increase the ability of the station to meet its operational requirements. The next step in designing the status monitor is therefore to describe the operational requirements of the station. This step is described in Section 2.2.

The main operations which a status monitor may perform to meet the defined objective are as follows:

(1) Failure* determination - This operation is to determine if the station is capable of operating within prescribed tolerances. This includes determining if all interfaces between sybsystems are properly configured and that the equipments are capable of performing their required function. This operation must be performed before corrective action can be taken. The corrective action may take the form of repairing the malfunction, replacing the faulty unit with a good one, or notifying operation-control that the station cannot meet the mission requirement, (then operation-control could take some corrective action like assigning the function to a back-up station). No matter which action is taken the probability of meeting the mission requirements will be increased.

(2) Failure isolation - In case of an indicated failure, information concerning the location of the faulty item is provided. This operation has the effect of decreasing the down-time required to correct the indicated failure, again increasing the probability of meeting the mission requirements.

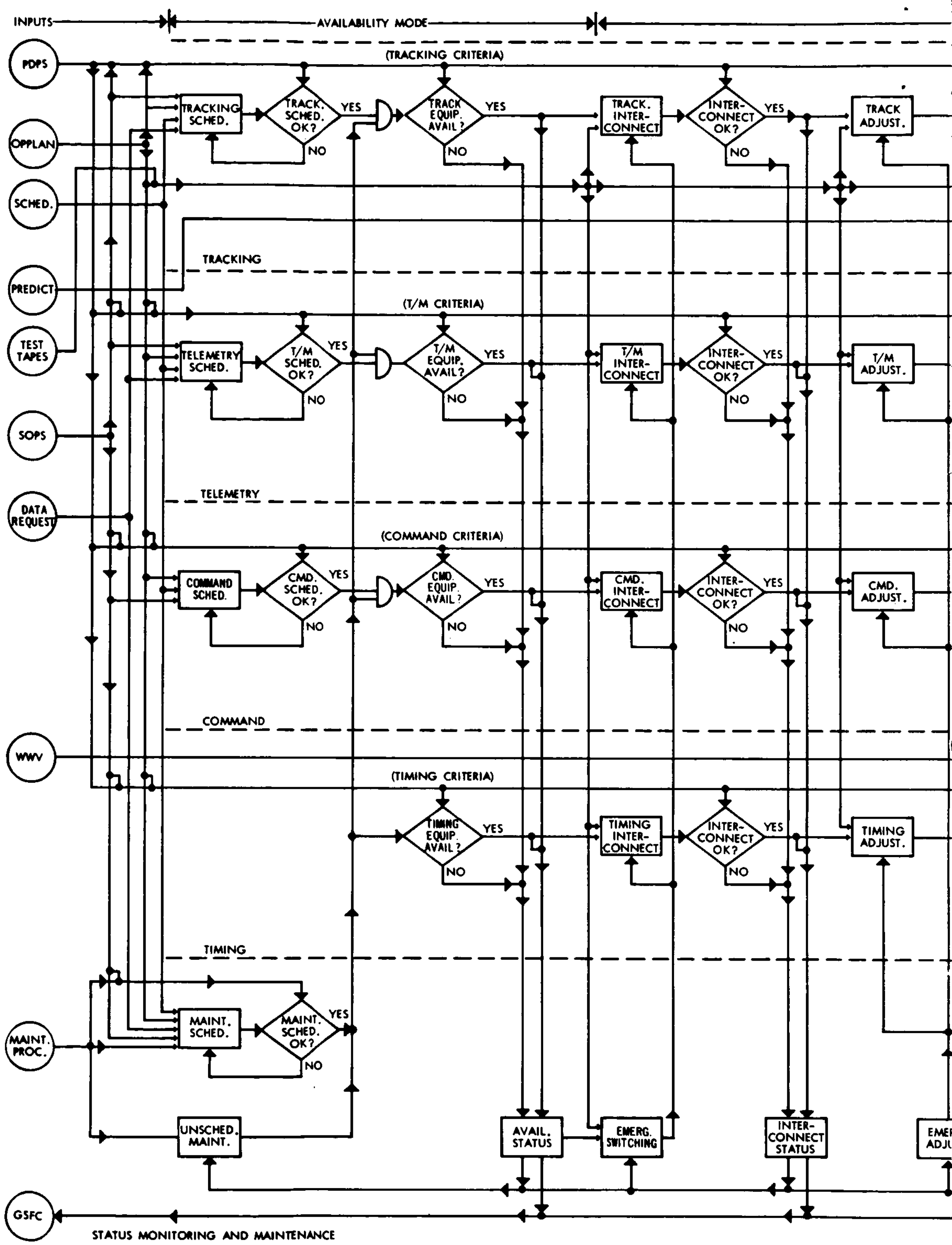
(3) Failure prediction - This is the operation of recognizing incipient failures in the system. This operation is accomplished by determining parameter drift and drift rates. This operation has the effect of decreasing the number of failures thus also, increasing the probability of meeting the mission requirements.

2.2 Step 2 - Describe the Operational Requirements of the Ground Station

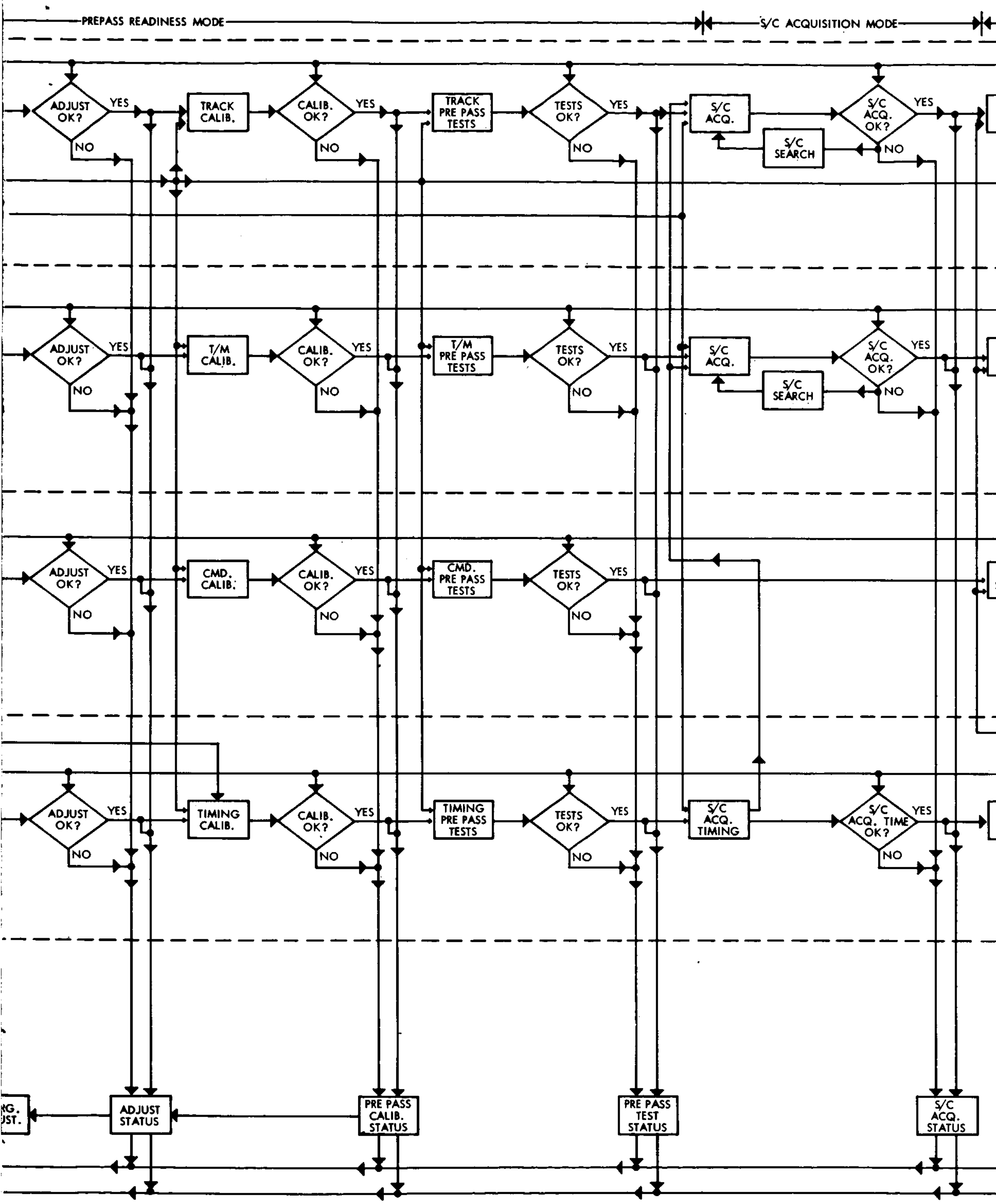
Operational requirements are those functions which the ground station must perform to accomplish all its mission objectives.

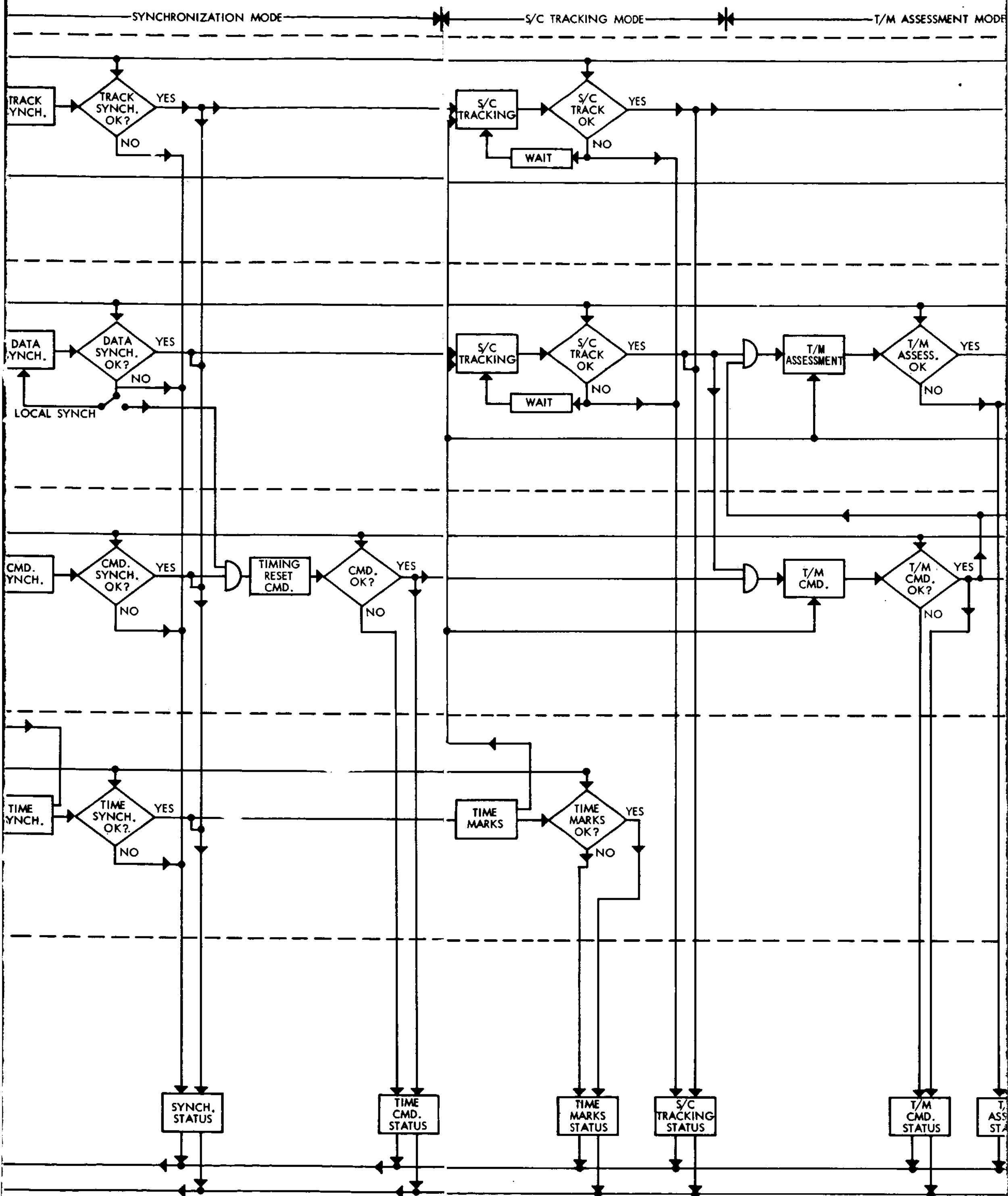
The complete operation of the NTTF is shown in Figure 3. As illustrated, the station operation has been separated into five functions (tracking, telemetry, command, timing, and monitoring and maintenance). Figure 3 has also been divided into the various modes in which the station operates. These modes (availability, prepass readiness, spacecraft (S/C) acquisition, telemetry (T/M)

*Failure is defined here to mean any malfunction which prevents the system from meeting its total mission requirements.

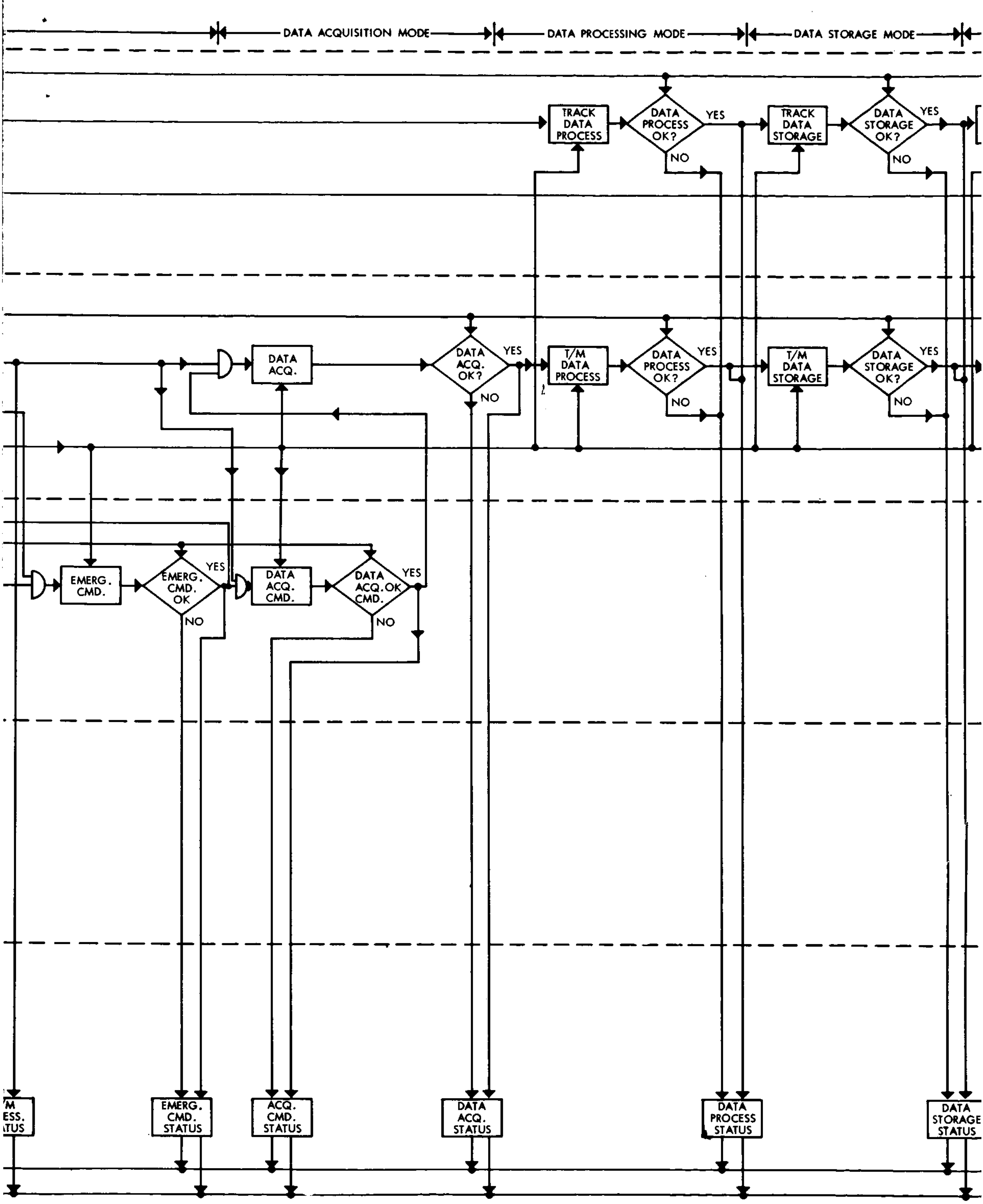


INPUTS
AVAILABILITY MODE
PDPS
OPPLAN
SCHED.
PREDICT
TEST TAPES
SOPS
DATA REQUEST
WWV
MAINT. PROC.
GSFC
(TRACKING CRITERIA)
TRACKING SCHED.
TRACK. SCHED. OK?
TRACK EQUIP. AVAIL?
TRACK. INTER-CONNECT
INTER-CONNECT OK?
TRACK ADJUST.
TRACKING
(T/M CRITERIA)
TELEMETRY SCHED.
T/M SCHED. OK?
T/M EQUIP. AVAIL?
T/M INTER-CONNECT
T/M ADJUST.
TELEMETRY
(COMMAND CRITERIA)
COMMAND SCHED.
CMD. SCHED. OK?
CMD. EQUIP. AVAIL?
CMD. INTER-CONNECT
CMD. ADJUST.
COMMAND
(TIMING CRITERIA)
TIMING EQUIP. AVAIL?
TIMING INTER-CONNECT
TIMING ADJUST.
TIMING
MAINT. SCHED.
MAINT. SCHED. OK?
UNSCHED. MAINT.
AVAIL. STATUS
EMERG. SWITCHING
INTER-CONNECT STATUS
YES
NO
STATUS MONITORING AND MAINTENANCE


PREPASS READINESS MODE
S/C ACQUISITION MODE
ADJUST OK?
YES
NO
TRACK CALIB.
CALIB. OK?
TRACK PRE PASS TESTS
TESTS OK?
S/C ACQ.
S/C SEARCH
S/C ACQ. OK?
T/M CALIB.
T/M PRE PASS TESTS
CMD. CALIB.
CMD. PRE PASS TESTS
TIMING CALIB.
TIMING PRE PASS TESTS
S/C ACQ. TIMING
S/C ACQ. TIME OK?
RG. JST.
ADJUST STATUS
PRE PASS CALIB. STATUS
PRE PASS TEST STATUS
S/C ACQ. STATUS


SYNCHRONIZATION MODE
S/C TRACKING MODE
T/M ASSESSMENT MODE
TRACK SYNCH.
TRACK SYNCH. OK?
YES
NO
S/C TRACKING
S/C TRACK OK
WAIT
DATA SYNCH.
DATA SYNCH. OK?
LOCAL SYNCH
T/M ASSESSMENT
T/M ASSESS. OK
CMD. SYNCH.
CMD. SYNCH. OK?
TIMING RESET CMD.
CMD. OK?
T/M CMD.
T/M CMD. OK?
TIME SYNCH.
TIME SYNCH. OK?
TIME MARKS
TIME MARKS OK?
SYNCH. STATUS
TIME CMD. STATUS
TIME MARKS STATUS
S/C TRACKING STATUS
T/M CMD. STATUS

5-3


DATA ACQUISITION MODE
DATA PROCESSING MODE
DATA STORAGE MODE
TRACK DATA PROCESS
DATA PROCESS OK?
YES
NO
TRACK DATA STORAGE
DATA STORAGE OK?
DATA ACQ.
DATA ACQ. OK?
T/M DATA PROCESS
T/M DATA STORAGE
EMERG. CMD.
EMERG. CMD. OK
DATA ACQ. CMD.
DATA ACQ. OK CMD.
EMERG. CMD. STATUS
ACQ. CMD. STATUS
DATA ACQ. STATUS
DATA PROCESS STATUS
DATA STORAGE STATUS

6-1

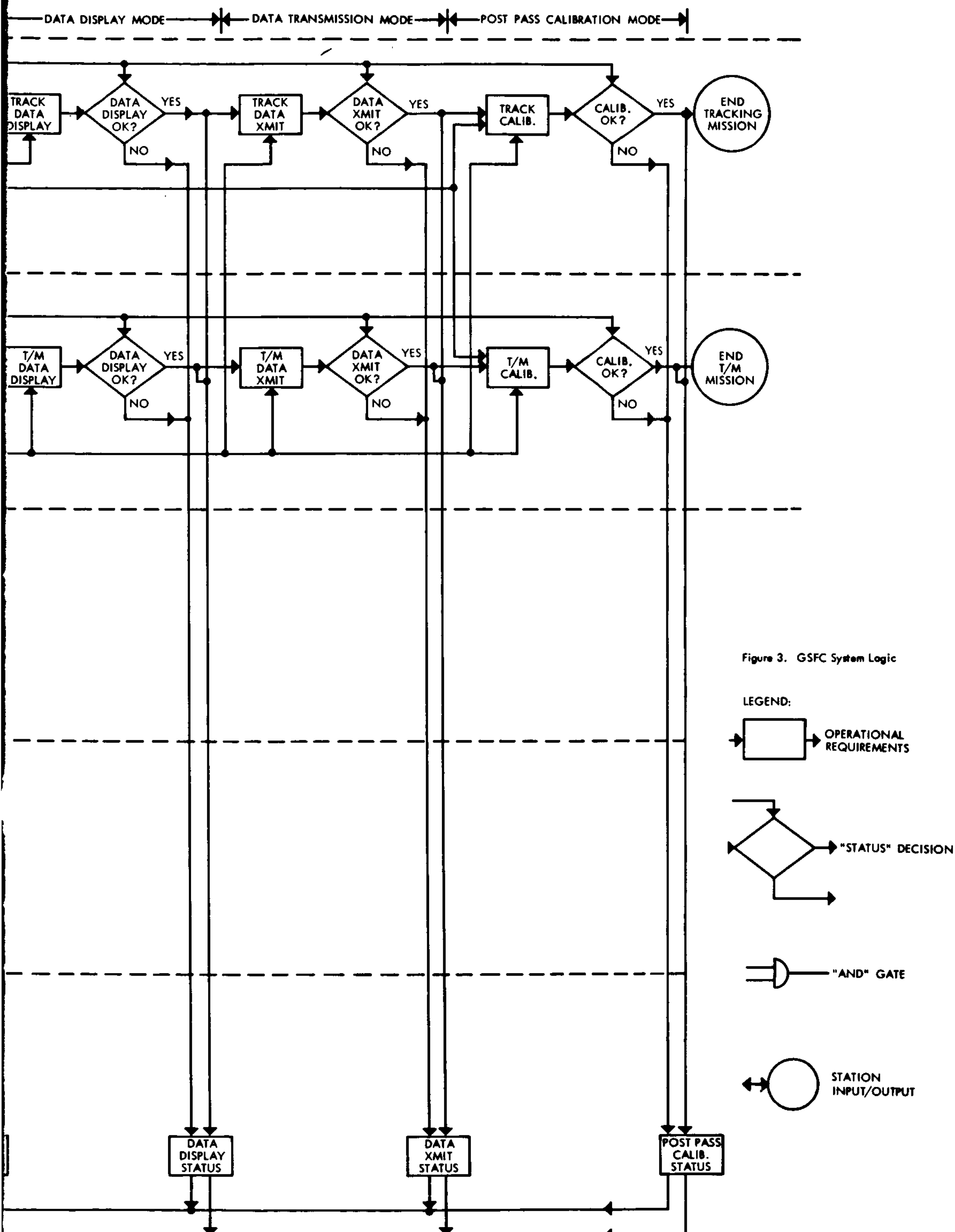


Figure 3. GSFC System Logic

assessment, etc.), are indicated at the very top of Figure 3. The operational requirements necessary for the station to perform each mode are indicated as rectangles on Figure 3.

The information needed to construct Figure 3 was obtained by a review of the STADAN Orientation Manual, GSFC Operations Plans, and on-site procedures.

This step, of describing on paper the operational requirements, is quite often left out of the intuitive design approach. When dealing with systems this step becomes necessary as it provides several important "bookkeeping" functions.

By setting down operational requirements on paper there is less chance of omitting any requirements. This step also enables recognition of interfaces between the various operations (e.g. while the status monitor design being considered is only for the telemetry portion of the station, Figure 3 indicates there exists interfaces which must be considered with the command and timing operations). Also indicated in Figure 3, represented as circles, is the input/output functions of the station (e.g. station reporting requirements and source of operating requirements).

The accomplishment of this step provides the basis for specifying performance indicators, Step 3.

2.3 Step 3 - Specify Measurable Quantities Which Most Directly Represent the Operational Requirements (performance indicators)

For each operational requirement, represented as rectangles in Figure 3, measurable quantities which most directly represent the requirements are derived. These measurable quantities are called "performance indicators."

Figure 4 illustrates the derivation of some performance indicators from the operational requirements. As illustrated, sometimes the requirements must be broken into sub-requirements before a measurable indicator of performance is derived. Thus there will be one or more performance indicators for each operational requirement.

The performance indicators are determined by reviewing the operational requirements (from Figure 3) and the hardware used in the system to accomplish the operational requirements (from equipment manuals).

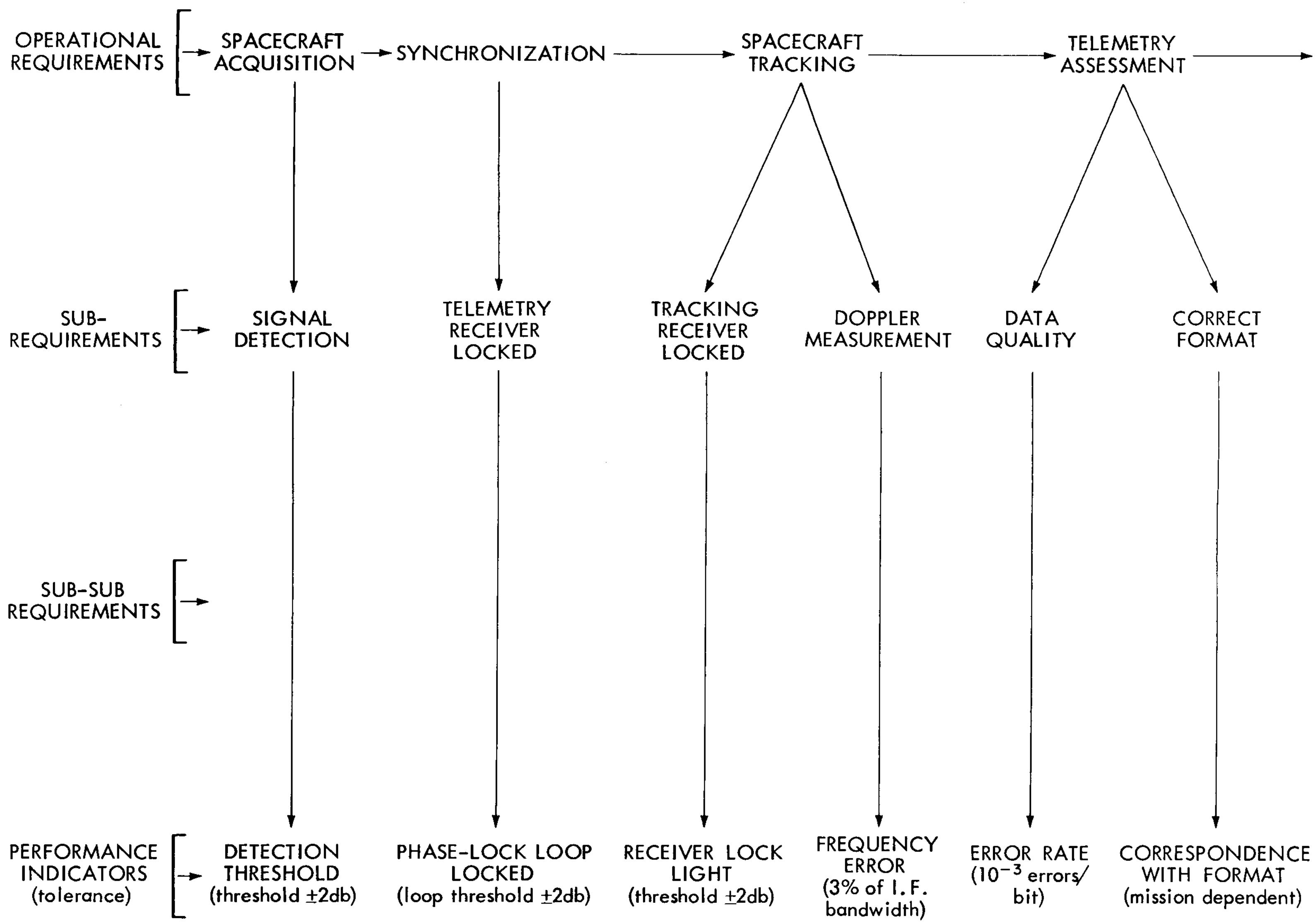


Figure 4. Development of Performance Indicators

With the accomplishment of this step the designer has specified the measurable quantities which indicate that the station is able to meet its operational requirements.

The next step in this design process is to develop methods of measuring the performance indicators or measuring other parameters which are related to the performance indicators.

2.4 Step 4 - Develop Methods of Measuring the Performance Indicators and, As An Alternate, Parameters Related to the Performance Indicators

Performance indicators can be measured directly or a measurement of some other quantity which relates to the performance indicators can be made. Some measurement configuration may be quite effective in its ability to determine the status of the performance indicators. Alternatively, other configurations may not be as effective but may be considerably cheaper to implement. The designer is thus faced with the age-old tradeoff problem of determining how much performance should he buy.

This step requires "good hard-headed engineering" and a detailed analysis of the equipment and operations. Here again the designer needs some way of keeping track of the individual detailed measurements while maintaining a complete overall picture of the alternate design configurations. The method of performing this bookkeeping is through the development of a measurement network diagram together with a table describing the measurement details.

An example of a trivial measurement network is illustrated in Figure 5. On Figure 5 measurements 1 and 2 represent two performance indicators. Alternate to measurement 1 measurements 3 and 4 could be made. Measurements 6 and 4 is another alternative to measurement 1. Also illustrated is a case where one measurement (9) is an alternative to measuring performance indicators 1 and 2.

Corresponding to each measurement in the measurement network is an entry in a table which describes how and where the measurement is performed.

The next step in solving the tradeoff problem is to specify appropriate measures of effectiveness and cost with which to make the evaluation.

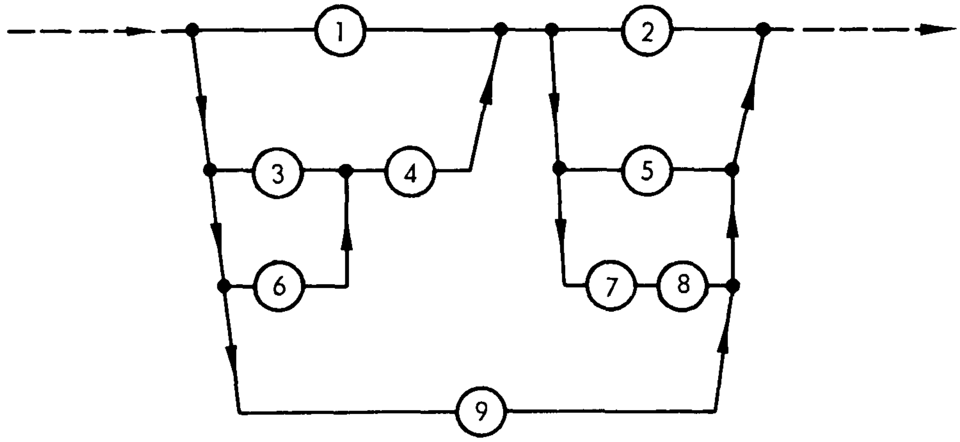


Figure 5. Example of a Measurement Network

2.5 Step 5 - Specify Measures of Effectiveness and Cost to be Used in Rating the Methods of Measuring the Performance Indicators and Their Alternates

The selection of the appropriate measures of effectiveness and cost is largely a matter of intuition (otherwise known as good hard-headed engineering). Here again, by putting these factors down on paper one is made aware of the reasons why a particular configuration was selected over others.

The measures of effectiveness (or effectiveness factors) for a status monitor are:

(a) How well the parameters monitored reflect variation of the performance indicators (these are called sensitivity factors).

(b) How well the parameters monitored recognize those items which exhibit a relatively high failure rate (these are called reliability factors).

(c) Are the parameters which are most important to the overall mission success monitored (these are called dependency factors).

(d) The amount of uncertainty about the status of the station that can be resolved in the least amount of testing time (these are called time factors).

The measures of costs (or cost factors) for a status monitor are:

(a) Cost of equipment procurement;

(b) Cost of implementing the status monitor system;

(c) Cost of operating and maintaining the status monitoring system;

(d) Cost of data gathering and display of the status information.

If some measures of effectiveness (or cost) are more important than others, relative weightings can be assigned to the different effectiveness (cost) factors to reflect this in the tradeoff analysis.

The methods for arriving at the various effectiveness factor ratings are as follows:

(a) Sensitivity factors - The theoretical relation between the measured parameter and the related performance indicator is used to estimate the sensitivity rating. This theoretical relationship may exist in the form of an equation, graph, table or it may need to be arrived at empirically.

(b) Reliability factors - Reliability ratings can be obtained from failure data, or if non-existent, from a reliability analysis using a parts count or a monte-carlo simulation, etc.

(c) Dependency factors - Dependency ratings are obtained from an analysis of the station configuration and the operational requirements.

(d) Time factors - Ratings of time factors are the result of test set-up time, testing time, and status interpretation time. Methods for estimating these time factors may require performing some empirical tests and possibly making a monte-carlo simulation.

The methods for arriving at the cost factor ratings are as follows:*

(a) Cost of equipment procurement - This rating is obtained from a survey of instrumentation costs and is the sum of the costs of the different test functions** used.

(b) Cost of implementation - A reasonable estimate of relative implementation cost appears to be simply the sum of the number of different test functions used.

*The reasoning behind these methods for arriving at cost factor ratings are presented in "A Study of Station Performance Criteria", by Operations Reasearch, Inc., under Contract NAS5-9910 for NASA-Goddard Space Flight Center.

**A test function is one particular measurement.

(c) Cost of operation and maintenance - The relative cost of operation can be estimated from the total number of test functions. The relative cost of maintenance is estimated by the number of different test functions.

(d) Cost of data gathering and display - A relative rating for this cost factor can be estimated from the total number of test functions.

For each measurement path in the network the effectiveness and cost rating of the measurement must be determined. There is one effectiveness rating for each measurement path. This rating is the sum of the ratings of the individual weighted effectiveness factors. There are two cost ratings for each measurement path. One cost rating is the sum of the ratings of the individual cost factors and is called the independent cost rating. The second cost rating takes into account the possibility of using the same instrumentation to make several measurements. This dependent cost factor is equal to the sum of all the cost factors less the cost of procurement of duplicate equipment.

2.6 Step 6 - Screen the Alternatives to Determine the Monitoring Configuration With the Greatest Effectiveness/Cost Rating

In this step the measurement network is analyzed to determine the set of measurements which exhibits the highest effectiveness/cost ratio.

If the measurement network is small, the selection could be made manually using such methods as matrix analysis or graph theory. If the measurement network becomes large the selection must utilize computer analysis.

The measurement network is a direct analog to the PERT (Program Evaluation and Review Technique) network. Thus, a standard PERT critical path program can be used. Part I of the PERT computer program calculates the "best" path as a free running program (that is without constraints on effectiveness or cost). If it is desired to place constraints on either minimum effectiveness or maximum cost, or both, the PERT-Part II (PERT with constraints) program is used.

In this program the computer goes through all possible paths, keeping track of both dependent and independent cost factors, and prints out the path which exhibits the highest effectiveness/cost ratio. This path makes up the best of the alternate sets of tests for monitoring the status of the telemetry portion of the NTTF.

Appendix A is a description of the optimum set of tests, as determined by the cost-effectiveness analysis, for monitoring the status of the telemetry portion of the NTTF. This description is presented to give the reader who is familiar with the station operation an indication of how completely the tests monitor the status of the telemetry installation.

3. CONCLUSION

This design procedure provides all the advantages of an intuitive design since the steps taken in this cost-effectiveness design includes exactly the same steps taken in an intuitive design. However, by performing this more rigorous design procedure the following significant advantages are achieved:

(a) By putting down on paper the effectiveness and cost factors, the reasons for selecting a particular system design is made in terms meaningful to everyone;

(b) By setting down on paper the station operational requirements and the performance indicators the determination of what should be displayed to the operator can be easily and rationally made.

(c) By being forced to specify both the overall picture and the fine details, the designer can very easily determine how changes in the station configuration (or operation) affect the status monitor design. This fact will enable the status monitor to be efficiently modified to accommodate the station changes;

(d) By requiring that factors of sensitivity, reliability, time and cost be determined, the designer is made aware of any lack of available data needed to determine the various ratings. The designer then knows what experiments need to be made before a status monitor design can be confidently selected or what data should be reported and in what format, to easily provide for future generation status monitoring systems.

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APPENDIX A

DESCRIPTION OF THE SELECTED STATUS MONITOR TESTS

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STATUS MONITORING TESTS

Test Group A: Frequency Modulation (FM) Mission Tests.

1. Improvement Threshold Test.

This test is to determine the improvement threshold point as given by KTB + NF + 10db (where KTB is the received noise power and NF is the noise figure inherent to the system). The improvement threshold is defined as the point on the Signal-to-Noise Ratio (SNR)/Carrier-to-Noise Ratio (CNR) curve where the output SNR increases db-for-db with the input CNR. This test permits the determination of any degradations in the bandwidth (B) or the noise figure (NF) of the basic telemetry receiving system.

2. Combiner Performance Test.

This test is to determine whether the CNR contributed by each received channel, at the improvement threshold point, is equal and that the two receiver outputs are being combined properly.

3. Non-Linear Noise Measurement Test.

This test is to determine, at the combiner output, the total phase non-Linearities that may occur within the receiving system.

4. Automatic Frequency Control (AFC) Loop Dynamic Response Test.

The combiner output is monitored to determine that the AFC loop dynamic response is capable of handling the doppler shifted transmission from any spacecraft.

Test Group B: Phase Modulation (PM) Mission Tests.

1. Acquisition Threshold Test.

This test will show system sensitivity and variations in the phase-lock loop bandwidth by determining the carrier power required to achieve lock and to maintain lock.

2. Combiner Performance Test.

(a) This test will be to determine the improvement, over single receiver operation, provided by the combiner over the range of lock threshold to saturation, and

(b) To determine that the combiner switches properly at low CNR's.

3. Doppler Extracting Test.

This test will be to determine the ability of the Electrac Phase-locked Demodulator to extract and record the doppler phase shift.

4. Non-Linear Noise Measurement Test.

This test will be to determine, at the combiner output, the total phase non-linearities that may occur within the receiving system.

Test Group C: Baseband Equipment Validation Tests.

1. Pulse Code Modulation (PCM) Validation Tests.

A test at the output of the (PCM/DHE) to determine the PCM error rate vs CNR, at a given confidence limit, through the complete receiving system, tape recorders, and PCM/DHE. This test is applicable to all Time Division Multiplex signals.

2. Pulse Frequency Modulation (PFM) Validation Test.

A check at the chart recorder output to determine the saturation, noise and non-linearities of the PFM system performance. (The PFM system includes telemetry receiver, combiner, subcarrier multiplexer/demultiplexer, and chart recorders.) This test is applicable to all Frequency Division Multiplex signals.

3. Antenna and Servo Performance Test.

To determine the correct electrical and mechanical operation of the antenna and servo tracking loop. (The antenna, tracking receiver and servo equipment are checked.)

APPENDIX B

COST-EFFECTIVENESS ANALYSIS: AN APPRECIATION

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COST-EFFECTIVENESS ANALYSIS: AN APPRECIATION

E. S. Quade

The RAND Corporation
Santa Monica, California

October 1965

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COST-EFFECTIVENESS ANALYSIS: AN APPRECIATION

E. S. Quade

October 1965

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COST-EFFECTIVENESS ANALYSIS: AN APPRECIATION

E. S. Quade*
The RAND Corporation
Santa Monica, California

This paper attempts to clarify the nature and scope of cost-effectiveness analysis and to point out its proper role as an aid to decisionmaking. It discusses, in the context of national security problems, the reliability and limitations of such analyses and ways to improve its quality.

Introduction

Cost-effectiveness is not a catchword to suggest we are doing something new, for the need to consider cost in relation to effectiveness must have occurred to the earliest planners. What is novel, however, is the marvelous refinement of methods for relating cost to performance that has taken place in the last few years and the acceptance of these methods at high policy levels where they are often proposed as a panacea for all the ills of intricate decisionmaking.

Definitions

What is a cost-effectiveness analysis? Broadly defined (too broadly for my taste) it is any analytic study designed to assist a decisionmaker identify a preferred choice from among possible alternatives. In a military context, typical analyses might tackle such questions as the extent to which aircraft should be repaired at a depot rather than on the base; the possible characteristics of a new strategic bomber and whether one should be developed or not; whether tactical air wings or carrier task forces should be substituted for U.S. ground divisions in Europe; or whether we should modify the test ban treaty now that the Chinese Communists have nuclear weapons and, if so, how. One stage of each such analysis involves a comparison of alternative courses of action in terms of their costs and their effectiveness in attaining some specific objective. This is cost-effectiveness analysis, narrowly defined. Usually this comparison takes the form of an attempt to minimize the cost implications subject to some mission requirement (which in broad problems is not likely to be measurable in dollar terms) or, conversely, to maximize some physical measure of performance subject to a budget constraint.

Since such comparisons receive the lion's share of attention by the participants, the entire study is often called a cost-effectiveness analysis. But this name emphasizes just one aspect of the study. For advice on broad questions of policy such as those related to national defense (where cost-effectiveness has been most extensively used), facets of the problem other than the comparison of alternatives may be of great significance. Among these are: the specification of sensible objectives, the determination of a satisfactory way to measure performance, the influence of considerations that can't be quantified, or the discovery of better alternatives.

Let me try to illustrate this last point with a homely example.

Suppose a family has decided to buy a television set. Not only is their objective fairly clear, but, if they have paid due attention to the advertisements, their alternatives are well-defined. The situation is then one for cost-effectiveness analysis. The only significant questions the family need answer concern the differences among the available sets in performance and cost. With a little care, making proper allowance for financing, depreciation, and maintenance, they can estimate, say, the five year procurement and operating cost of any particular set and do so with a feeling that they are well inside the ball park. They will discover, of course, that finding a standard for measuring the performance of the various sets is somewhat more difficult. For one thing, it may have many aspects--color quality, the option for remote control, portability, screen size, and so forth. But, ordinarily, one consideration--perhaps color--determines a price class. On this basis, one can look at color sets, compare costs against color quality, and determine a best buy.

Now suppose the family finds they have more money to spend and thus decide to increase their standard of living--a decision similar to one to strengthen the U.S. defense posture by increasing the military budget. This is a situation calling for a broader analysis. They first need to investigate their goals or objectives and look into the full range of alternatives--a new car, a piano, a trip to Europe. They then must find ways to measure how well these alternatives accomplish their goals and establish criteria for choice among them. Because the alternatives are so dissimilar, determining what they want to do is the major problem; how to do it and how to determine what it costs is a comparatively minor one.

In brief, to handle a broad problem adequately a study must look at the entire problem and look at it in its proper context. Characteristically, such an analysis will involve a systematic investigation of the decisionmaker's objectives and of the relevant criteria; a comparison--quantitative where possible--of the costs, effectiveness, risks, and timing associated with the alternative policies or strategies for achieving each objective; and an attempt to formulate better alternatives if those examined are found wanting. Although I prefer th

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name "systems analysis" for the broader analysis, in what follows I'll use the term cost-effectiveness for the full range, broad and narrow, of analytic approaches to aid a decisionmaker with problems of choice.

The Essence of the Method

What is there about an analytic approach that makes it better or more useful than other ways to furnish advice--than, say, an expert or a committee? In areas such as defense planning, where there is no accepted theoretical foundation, advice obtained from experts working individually or as a committee depends largely on judgment and intuition. So does the advice from cost-effectiveness analysis. But the virtue of analysis is that it permits the judgment and intuition of experts in many fields to be combined systematically and efficiently to yield results that can transcend those of any individual or committee. The essence of the method is to construct and operate within a "model"--a simplified, stylized representation of the real world which abstracts the cause and effect relationships essential to the question being studied. Such a model--which may take such varied forms as a set of mathematical equations or a computer program, a war game, or even a purely verbal scenario--introduces a precise structure and terminology that serve primarily as a means of communication, enabling the participants in the study to make their judgments in a concrete context and with proper reference to the judgment of others. Moreover, through feedback--the results of computation, the countermoves in the war game, or the critique of the scenario--the model helps the experts to revise their earlier judgments and thus to arrive at a clearer understanding of the problem and its context.

The central importance of the model (or the models, for it may be inappropriate or absurd to attempt to incorporate all aspects of a problem in a single formulation) can be seen most readily, perhaps, by looking at its role in the choice of alternatives.

Having formulated and researched the problem --that is, clarified the issues, limited the extent of the inquiry, searched out the necessary data and relationships, discovered what objectives the decisionmaker is, or should be, trying to attain, and how to measure the extent to which they are, in fact, attained, and built various models--the process is somewhat as follows. (See chart.) To begin, the various alternatives or means by which one can hope to attain the objectives (which may have to be discovered or invented as part of the analysis) are examined by means of the models. These models tell us what we can expect from each particular alternative with respect to such things as attrition, reliability, and so forth, and what the costs are. The measure of effectiveness then tells us the extent to which each objective is attained. A criterion or rule of choice can then be used to weigh the costs against performance and thus arrange the alternatives in order of preference.

This process may be difficult to carry out. For instance, consider the estimation of total system reliability. Often this is represented by the mean time between failures (MTBF), calculated by taking the reciprocal of the sum of the reciprocals of the subsystem MTBF's. The exponential distribution is then used to obtain the probability that no system failure will occur in a time period. This simple scheme involves at least four tacit assumptions:

- The time between failures is exponentially distributed,
- Failures of subsystems are independent,
- A subsystem failure implies a system failure,
- Subsystems are utilized equally in time.

Ideally, the equations which express reliability should account for subsystem failure rates, redundancies, dependencies, and utilization. While complicated, this is not beyond the capabilities of a computer. But the estimates of the subsystem failure rates themselves depend on partial measurements and intuitive judgments of the influence of temperature, humidity, dust, shock, stress, vibration, operating cycle, and the environment. The end result may be that predictions from the reliability model are highly uncertain.

In fact, things are seldom tidy. Too often alternatives are not adequate to attain the objectives; measures of effectiveness do not really measure the extent to which the objectives are attained; the predictions from other models, as well as from the reliability model, are full of uncertainties; and other criteria which look almost as attractive as the one chosen may lead to a different order of preference. When this happens, no one is happy and we must take another approach. Dissent and discussion force modification of original ideas about objectives and alternatives are redesigned. The key to successful analysis is a continuous cycle of formulating the problem, selecting the objectives, designing better alternatives, collecting data, building new models, weighing cost against performance, questioning assumptions and data, reexamining the objectives, opening new alternatives, and so on until satisfaction is obtained or time or money forces a cutoff.

The Limitations

Analysis of this type is not only difficult to do well but even when well done there are many limitations. Some of these are due to limitations inherent in all analysis of choice. Others are due to the difficulties encountered in coping with such things as the varying times at which alternatives become available or uncertainty about the enemy. Still others are flaws or errors which, hopefully, will disappear as we learn to do better and more thorough analyses. The most dangerous source of defects, however, is an attention bias. It is frequently caused by the cherished beliefs or unconscious adherence to a "party line" that all organizations foster to some extent.

It is important to remember that all analysis of choice falls short of scientific research. No matter how we strive to maintain standards of scientific inquiry or how closely we attempt to follow scientific methods, we cannot turn cost-effectiveness analysis into science. Its objective, in contrast to that of science, is primarily to recommend--or at least to suggest--policy, rather than merely to understand and predict. Like engineering, it seeks to use the results of science to do things well and cheaply. Yet it differs from ordinary engineering in its enormous responsibility, in sometimes being forced by the nature or urgency of a problem to substitute intuition for verifiable knowledge, in the unusual difficulty of appraising--or even discovering--a value system applicable to its problems, and in the absence of ways to test its validity.

Except for this inability to verify, cost-effectiveness analysis may still look like a purely rational approach to decisionmaking, a coldly objective, scientific method free of preconceived ideas and partisan bias and judgment and intuition. But it isn't really. Human judgment is used in designing the analysis: in deciding what alternatives to consider, what factors are relevant, what the interrelations between these factors are, and what numerical values to choose. Moreover, it is human judgment which analyzes and interprets the results of the analysis. This fact --that judgment and intuition permeate all analysis--should be remembered when we examine the results that come, with apparent high precision, from analysis.

But it is the inherent limitations of the analysis, not errors, that confine it to an advisory role. I shall single out three of them for further comment: analysis is necessarily incomplete; measures of effectiveness are inevitably approximate; and ways to predict the future are lacking.

<u>Analysis is necessarily incomplete</u>

Time and money costs obviously place sharp limits on how far any inquiry can be carried. Other costs are important here too. For instance, we would like to find out what the Chicoms would do if we put an end to all military aid to Southeast Asia. One way to get this information would be to stop such aid. But while the immediate dollar cost would be low, the likelihood of other costs occurring in time precludes at once this type of investigation.

Still more important, however, is the general fact that even with no limitations of time or money analysis can never treat all the considerations that may be relevant. Some are intangible. For example, how some unilateral U.S. action will affect NATO solidarity or whether Congress will accept military economies that disrupt cherished institutions such as the National Guard or radically change the pattern of domestic military spending are questions that are hard to handle objectively. Considerations of this type can, and possibly should, play as important a role in the choice of alternative force postures as any idealized war outcome calculations. But ways to measure these things even approximately don't exist today and they must be handled intuitively Other issues involve moral judgments: whether national security is better served by an increase in the budget for defense or for welfare or under what circumstances the preservation of an ally is worth the risk of general war. The analyst can apply his own judgment and intuition and that of others to these considerations (at least to those of which he is aware!), thus making them part of the study and <u>bringing them to the attention of the decisionmaker</u>. But the man with the responsibility will rightly insist on applying his own.

<u>Measures of effectiveness are approximate</u>

In military cost-effectiveness comparisons, measures of effectiveness are at best reasonably satisfactory approximations for indicating the attainment of such vaguely defined objectives as deterrence or victory. Sometimes the best that can be done is to find measures which point in the right direction. Consider deterrence, for instance It exists only in the mind--and in the enemy's mind at that. We cannot, therefore, measure directly the effectiveness of alternatives we hope will lead to deterrence, but must use instead approximations such as the potential mortalities that we might inflict or the roof cover we might destroy. Consequently, even if a comparison of two force postures indicated that one could inflict 50 per cent more casualties on the enemy than the other, we could not conclude that this posture supplies 50 per cent more deterrence. In fact, since it may be important not to look too dangerous, we find arguments that the posture which threatens the greatest number of casualities may provide the least deterrence!

Moreover, we can't be as confident about the accuracy of our estimates of effectiveness as we are about our cost estimates. It is the opinion of analysts who are studying the problem of estimating potential casualties that these estimates could easily be off by factors of three or four.

In brief, we don't know how to translate a capability to create casualties (as perceived by the enemy) into deterrence, we don't know how they will compute the casualty-producing capability of our forces, and we don't even know how to do it ourselves very accurately.

Don't misunderstand me--the determination of even the dollar costs of a military action is not simple, and to trace out all the resource implications of forces and weapons that are as yet only concepts is difficult. But once we decide <u>what</u> we are costing, we can do fairly well.

<u>No satisfactory way to forecast the future exists</u>

While it is possible to forecast events to come in the sense of mapping out possible futures, there is no satisfactory way to predict a single future in terms of which we can work out the best system or determine an optimum policy. Consequently, we must consider a range of possible futures or contingencies. In any one of these we may be able to designate a preferred course of action, but we have no way to determine one for the entire range of possibilities. We can design a force structure for a particular war in a particular place, but we have no surefire way to work out a structure that is good for the entire spectrum of future wars in all the places they may occur.

Consequently, defense planning is rich in the kind of analysis that tells what damage could be done to the United States given a particular enemy force structure, but it is poor in the kinds of analyses that evaluate how we will actually stand in relation to the Soviets in years to come.

The Virtues

In view of its defects, is cost-effectiveness reliable? If reliability has its colloquial meaning of being a measure of whether it works or not, the answer is yes. This is certainly the opinion of the decisionmakers who have made extensive use of it. As Charles J. Hitch, then Assistant Secretary of Defense, expressed it:

> In a way, it is quite ironic that the very people who are so insistent that they want the "best and most modern" in Defense hardware, are opposed to the "best and most modern" in Defense analysis and decision-making techniques.[1]

The fact that we cannot perform cost-effectiveness analyses with anything near 100 per cent confidence of perfection is no reason to rule out their use. The real argument for their use is that they provide sounder advice than the alternatives.

These alternatives have defects too. One alternative is pure intuition. It is in no sense analytic, since no effort is made to structure the problem or to establish cause and effect relationships and use them to arrive at a solution. The process is to learn everything possible about the problem, to "live with it," and to let the subconscious provide the solution.

Between pure intuition, on the one hand, and cost-effectiveness analysis, on the other, there are other sources of advice that can, in a sense, be considered to employ analysis, although the analysis is ordinarily less systematic, explicit, and quantitative. One alternative is to turn to an expert. His opinion can, in fact, be very helpful, if it results from a reasonable and impartial examination of the facts, with due allowance for uncertainty, and if his assumptions and chain of logic are made explicit. For if it is explicit, others can use his information to form their own considered opinion. But an expert, particularly an unbiased expert, may be hard to find. Another way of handling a problem is to turn it over to a committee. Committees, however, are much less likely than experts to make their reasoning explicit, since their findings are usually obtained by bargaining.

The danger is not that analysis will give the wrong advice; it may, of course, but without analysis the chances are much higher. And for some questions analysis is essential: without calculation there is no way to discover how many missiles may be needed to destroy a target system, or how arms control may affect security. Analysis offers an alternative to "muddling through"; to waiting until one can see the problem clearly and then attempting to meet the situation. Delay can be hazardous; in the world today, there could be a crisis or a weapon that could not be handled in this way. This is not to say that every aspect of such problems can be quantified or that analysis is without limitations, but only that it is not sensible to formulate policy without careful consideration of whatever relevant numbers can be discovered.

Let me draw an analogy between the decisionmaker using a study team for advice and a medical doctor using a clinical laboratory. Suppose, for example, our doctor is trying to decide whether to send his patient to a surgeon to have his stomach resected or to treat him medically for a gastric ulcer. The doctor is influenced by:

1. The technical findings of the laboratory crews. Like the decisionmaker, he might or might not be able to carry out these investigations himself, but it would not be economic for him to do so. He depends, therefore, on laboratory reports, some of which will be on cold slips of paper without comment or nuance--numbers alone. Others from the laboratory might write paragraphs or talk to the doctor or bring x-ray plates to discuss with him.

2. Observations or analyses the doctor makes himself. Some of these he puts in the form of written notes; those he can't write out he retains in his head.

3. Impressions of the risks and possibilities of success with various treatments. Some of these impressions are from his experience, others from medical reports.

Finally, like the decisionmaker, the doctor must make a judgment based on whatever facts or analyses he has. This judgment is the ultimate synthesis the doctor makes of the numerical tests, the written out but relatively diffused notes, the unrecorded conversations with technicians, and his own introspection. It is not a mere calculation, but is made on intuitive grounds. Sometimes a factor is overriding, but on the whole he just doesn't know. He could do more analysis, sometimes even risk the patient's life in order to guard it--call for a liver puncture or other dangerous procedures--but his inquiry can never be complete. His judgment, like that of every decisionmaker, must be made with uncertainties in mind.

It is easy, unfortunately, to exaggerate the degree of assistance that analysis can offer a policymaker. In almost every case, it can help him understand the relevant alternatives and the key interactions by providing an estimate of the costs, risks, and possible payoffs associated with each course of action. In so doing, the analysis may sharpen his intuition; it will certainly broaden his basis for judgment. This can almost always help the decisionmaker make a better decision than he would otherwise make, but the inherent limitations mean that a study can seldon demonstrate, beyond all reasonable doubt, that a particular course of action is best.

Now what about quality control? Because cost-effectiveness analysis is to a large extent art, it is pointless to expect success to follow from a set of definite rules. Reliability and quality control are not applicable to an art and a high degree of accuracy in an absolute sense is meaningless and impossible. The only way to insure that the work is well done and used with its limitations in mind is through a thorough critique by others. For no individual can hope to be completely objective. The most we can hope for is that they be honest in identifying their bias.

The Future

And finally, what of the future? Resistance to the use of cost-effectiveness analysis to help in broad problems is gradually breaking down. Government and industry planning have always involved more art than science; what is happening is that the art form is changing from an ad hoc, seat-of-the-pants approach based on intuition to one based on analysis supported by intuition and experience. With this change the computer is becoming increasingly significant--as an automaton, a process controller, an information processor, and a decision aid. Its usefulness in serving these ends can be expected to grow. But at the same time, it is important to note that even the best computer is no more than a tool to expedite analysis. Those advocates who hold that decisions can be made today solely by consideration of computer calculations are not only premature in their belief (to say the least), but have a basic misunderstanding of how such calculations must, in fact, always be used. Even in the narrowest decisions, considerations not subject to any sort of quantitative analysis can always be present. Big decisions, therefore, cannot be the automatic consequence of a computer program, of cost-effectiveness analysis, or any application of mathematical models.

For broad studies, involving force posture and composition or the strategy to achieve foreign policy objectives, intuitive, subjective, even ad hoc study schemes must continue to be used--but supplemented to an increasing extent by cost-effectiveness analysis. And as ingredients of this analysis, along with an increasing use of the computer for those problems where it is appropriate, in recognition of the need for a better treatment of the nonquantifiable aspects, a greater use of techniques for the better employment of judgment, intuition, and experience can be expected. These techniques: war gaming, "scenario" writing, and the systematic interrogation of experts are on the way to becoming an integral part of cost-effectiveness analysis.

Moreover, the scope will broaden. Cost-effectiveness has barely entered the domain of the social sciences, where in urban planning, in education, in welfare, and in other nonmilitary aspects of government we are faced with an abundance of challenges: how to alleviate the hardships of social change, how to provide food and comfort for the poor, how to improve the social institutions and the values of the affluent, how to cope with revolutionary innovations, and so on. Cost-effectiveness analysis[2] can help with these problems as well as those of industry and the military.

Concluding Remarks

And now to review. A cost-effectiveness analysis is an analytic study designed to assist a decisionmaker identify a preferred choice from among possible alternatives. It is characterized by a systematic and rational approach, with assumptions made explicit, objectives and criteria clearly defined, and alternative courses of action compared in the light of their possible consequences. An effort is made to use quantitative methods but computers are not essential. What is essential is a model that enables expert intuition and judgment to be applied efficiently. The method provides its answers by processes that are accessible to critical examination, capable of duplication by others, and, more or less, readily modified as new information becomes available. And, in contrast to other aids to decisionmaking, which share the same limitations, it extracts everything possible from scientific methods, and its virtues are the virtues of those methods. At its narrowest, cost-effectiveness analysis offers a way to choose the numerical quantities related to a weapon system so that they are logically consistent with each other, with an assumed objective, and with the calculator's expectation of the future. At its broadest, it can help guide national policy. But, even within the Department of Defense, its capabilities have as yet to be fully exploited.

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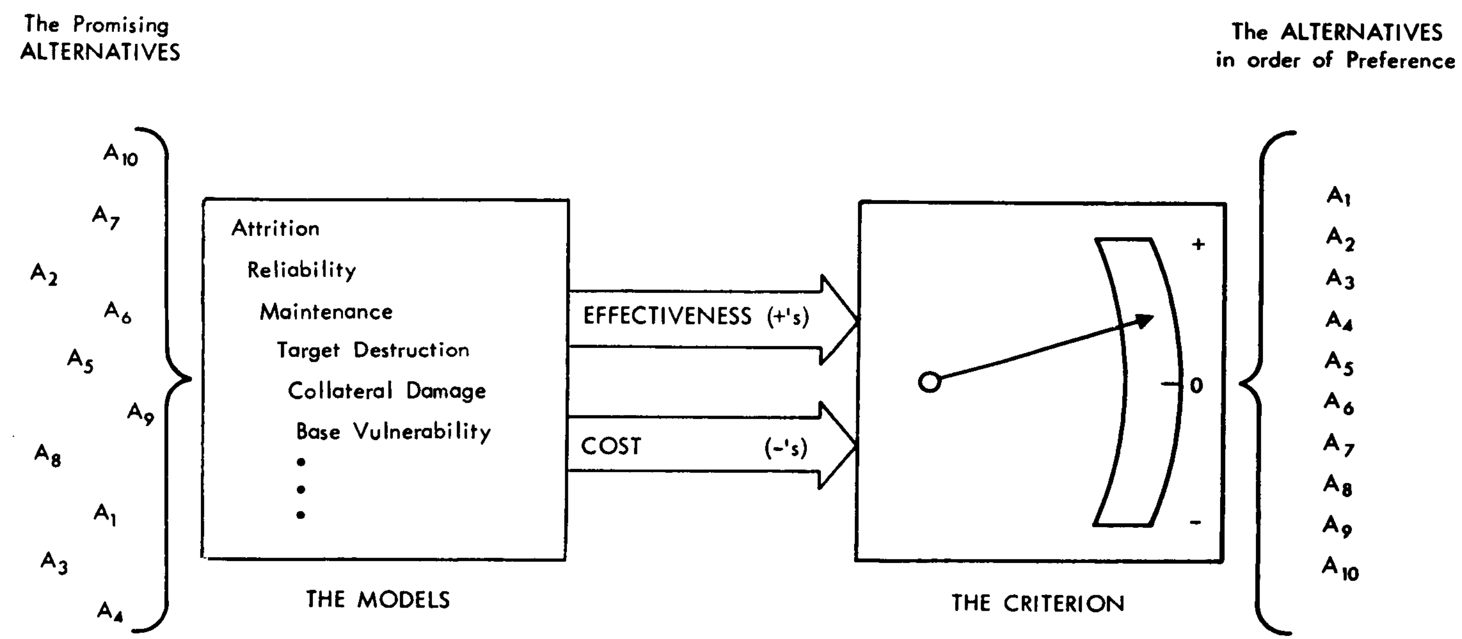

The structure of analysis