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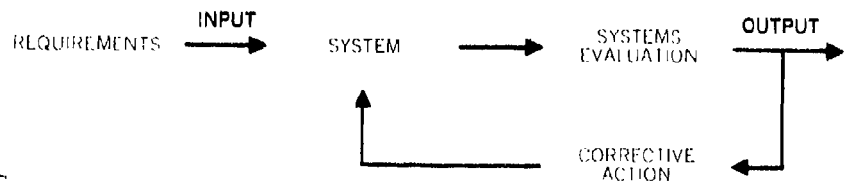
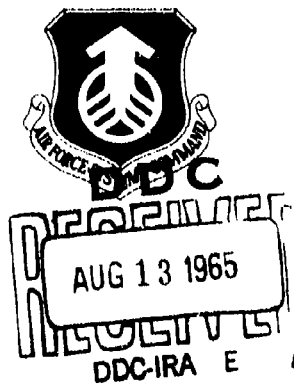
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**Weapon  
System  
Effectiveness  
Industry  
Advisory  
Committee**

**Chairman's  
Final Report  
AFSC-TR-65-6**

**JANUARY 1965**



**UNITED STATES AIR FORCE  
AIR FORCE SYSTEMS COMMAND**

# **SECURITY**

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WEAPON SYSTEM EFFECTIVENESS  
INDUSTRY ADVISORY COMMITTEE (WSEIAC)

FINAL SUMMARY REPORT

CHAIRMAN'S FINAL REPORT  
(INTEGRATED SUMMARY)

## FOREWORD

This final report presents a capsule summary and integration of the separate reports of the Weapon System Effectiveness Industry Advisory Committee (WSEIAC). For more detailed description and development of the theory, principle, and recommended practices proposed by the WSEIAC, it is suggested that the reader consult the individual task group reports, which are listed in the References and mentioned throughout this Volume.

Hq Air Force Systems Command is indebted to the many individuals in industry and in the government, and to their companies and offices for the support that made this task possible. The hard work and frequent personal sacrifices of the many task group members enabled a realization of many of the original WSEIAC objectives in just over a year's time.

The Chairman is particularly indebted to the Editorial Group which spent many long hours transforming the preliminary task group reports into the present volumes and in preparation of this Integrated Summary Report.

Members of this group were:

|                       |                                   |
|-----------------------|-----------------------------------|
| Mr. A. J. Monroe      | TRW Space Technology Laboratories |
| Mr. H. D. Voegtlen    | Hughes Aircraft Company           |
| Mr. F. N. Kanaga      | TRW Space Technology Laboratories |
| Maj F. H. Moxley, Jr. | Hq Air Force Systems Command      |

Preparation of the final manuscripts was performed by Mrs. Hendrik Groeneveld and Mrs. James Morrison.

Additionally the Chairman is indebted to Mrs. Robert Chaney of Hq Air Force Systems Command for her secretarial assistance in administering the WSEIAC program. Her untiring and faithful efforts contributed immeasurably to the success of the committee.

Publication of this report does not constitute official Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

APPROVED

  
William F. Stevens, Colonel, USAF  
Chief, Systems Effectiveness Division  
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## ABSTRACT

The principal findings, conclusions, and recommendations of the five WSEIAC Task Groups are presented in summary form. The system effectiveness problem is examined in light of the task group investigations. A fifteen-step procedure for cost-effectiveness assurance is presented. Application of the method and results to be expected in each phase of a system life-cycle are described. The impact on existing disciplines is examined. A section (Appendix IV) of this integrated summary contains abstracts and summaries of each of the ten reports submitted by the five Task Groups. Appendix I contains a more detailed treatment of the fifteen recommended tasks. Appendix II presents an example of application of this methodology shown for a hypothetical system in the Conceptual Phase. Finally, Appendix III is a glossary of effectiveness/cost-effectiveness terms.

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## SECTION I

### INTRODUCTION

The design and development of military systems has traditionally crowded the state-of-the-art in materials, devices, and technology. In recent times, designers have been faced simultaneously with even more novel demands and acutely limited test data. Performance requirements invariably include severe reaction times which can be met only by closely integrating personnel, procedures, and hardware. At the same time, program cost limitations, accelerated development schedules, and lack of opportunity for complete system tests prior to operational deployment have reduced the opportunity to obtain extensive operational usage data. Accordingly, what was once merely considered desirable is now considered mandatory --- an integrated methodology of system management using all available data both to pinpoint problem areas and to provide a numerical estimate of system effectiveness during all phases of the system life-cycle.

A general recognition of this situation at AFSC headquarters led to the formation of the Weapon System Effectiveness Industry Advisory Committee (WSEIAC). Although the Air Force Systems Command recognized the need for a common methodology to predict and measure system effectiveness, they realized that the problem affected too many other organizations to tackle the development of the methodology alone. Thus, they submitted a proposal to the Secretary of the Air Force to create a committee composed of both industry and Department of Defense personnel. The committee was formed 16 September 1963 by the AF Systems Command with the approval of Secretary of the Air Force, Mr. E. Zuckert, for the purpose of "providing technical guidance and assistance to the Commander, AFSC, in the development of a technique to apprise management of current and predicted system effectiveness at all phases of system life."

The committee was composed of five task groups of approximately ten members each. The industry members were "hired" as special government employees and required Secretary of Air Force approval also. They served

without compensation, and were subject to rigid conflict-of-interest regulations. From the Air Force there were members of the Systems Command, the Logistics Command, the Air Training Command, the Air University, and some using commands. In addition, there was coordination with the Army, Navy, NASA and the Department of Defense through participating observers.

The objectives of each task group were:

Task Group I

- Review present procedures for establishing system effectiveness requirements.
- Recommend a method for determining system effectiveness requirements which are mission responsive.

Task Group II

- Review existing documentation on system effectiveness.
- Recommend methods and procedures for measurement and prediction of system effectiveness in all phases of system life.

Task Group III

- Review current (Air Force) data collection and reporting systems.
- Recommend uniform procedures for periodic status reporting to assist all management decision levels.

Task Group IV

- Develop a set of basic instructions and procedures for conducting analysis for system optimization considering:
  - effectiveness
  - cost
  - program time scale.
- Refine current cost-effectiveness analysis techniques.

Task Group V

- Develop a management system designed to absorb and apply system effectiveness experience retention.

Technical reports covering each task group's work have been published.  
They are:

|                                   |                                                                                           |
|-----------------------------------|-------------------------------------------------------------------------------------------|
| AFSC-TR-65-1                      | Final Report of Task Group I <sup>(1)</sup><br>"Requirements - Methodology"               |
| AFSC-TR-65-2<br>(Vol. I, II, III) | Final Report of Task Group II <sup>(2, 3, 4)</sup><br>"Prediction - Measurement"          |
| AFSC-TR-65-3                      | Final Report of Task Group III <sup>(5)</sup><br>"Data Collection and Management Reports" |
| AFSC-TR-65-4<br>(Vol. I, II, III) | Final Report of Task Group IV <sup>(6, 7, 8)</sup><br>"Cost-Effectiveness Optimization"   |
| AFSC-TR-65-5<br>(Vol. I, II)      | Final Report of Task Group V <sup>(9, 10)</sup><br>"Management Systems"                   |

The Chairman's Final Report is a synopsis of the above technical reports. The purpose of the report is to integrate and present the results of the WSEIAC effort, and to show how these results relate to Air Force Systems Management. The report is presented in two volumes --- the present Integrated Summary (Volume II) and a very brief report which is a general summary (Volume I).

## SECTION II

### WHAT IS THE PROBLEM?

The accelerated pace of design, development and obsolescence of military systems in recent years has given rise to a series of problems in systems management. For example:

(1) Many of today's systems have a high unit cost. If, in the interest of economy, the national budget is to be held in line with national objectives, there must be a clear indication of both the cost and effectiveness of a proposed system long before the decision is made to produce the system and put it into operational use. Thus, there is a clear need to predict system and cost-effectiveness as early in the system life-cycle as possible.

High unit costs also lead to abbreviated test programs during the Acquisition Phase. Consequently, there is a large degree of uncertainty in the quality of the product in service use. Better methods of quantification are needed to reduce this uncertainty.

(2) Many of today's weapon systems tend to be "one shot" devices. As a result, adequate field "debugging" exercises are difficult to accomplish. There is less direct advance evidence as to the adequacy of a system. It is becoming increasingly necessary to rely on indirect evidence for assurance of effectiveness. The buyer, usually the Air Force Systems Command, must have a way to assess and assure the ability of a system to meet the requirements of the user, usually an operational command.

(3) Very few deny the necessity of defense. Yet, in the past few years there has been ever greater emphasis to reduce peacetime defense costs. At the same time there has been additional emphasis to increase wartime effectiveness. Maximizing effectiveness and minimizing costs at the same time is not possible, since it is impossible to maximize and minimize two dependent variables at the same time. Thus, the real problem is to obtain as efficient a defense posture as possible within the constraints of cost and effectiveness, or stated another way, to optimize

cost when the effectiveness is constrained or to optimize effectiveness when the cost is constrained. This is generally referred to as cost-effectiveness optimization. Optimization means allocating the national resources in a way that withstands the critical vision of hindsight. This is an extremely difficult problem since the defense posture is developed in the presence of risk and uncertainty. Thus it is essential to seek and use the best available methods for cost-effectiveness optimization.

(4) Many programs and studies have been conducted under the name of system effectiveness, operational effectiveness, operational readiness, and like terms, but which all referred to the same problem. A need existed to gather together people with the most knowledge in this problem area in order to standardize definitions, terminology, and a method of attack.

(5) Finally, there is the problem of establishing quantitative requirements for complex systems, particularly when those requirements must be stated in probabilistic terms. The severity of this problem may be judged from the following WSEIAC observation:

The minimum acceptable requirements of a certain recent SOR are given piecemeal in terms of separate probabilities and performance limits without obvious relation one to another. When combined in an overall system effectiveness number (along WSEIAC lines) these requirements suggest that if this system works less than 4 times out of 100, it is acceptable.

These, then, are some of the problems for which the WSEIAC sought solutions.

### SECTION III

#### THE WSEIAC APPROACH TO THE PROBLEM

When a new system is to be constructed or an old one put to new purposes, there are two diametrically opposed ways of proceeding:

- immediately commit resources to an intuitively plausible (re)design and surmount the problems as they arise, or
- explore in the "mind's eye" the consequences of the (proposed) system characteristics in relation to mission objectives before irrevocably committing resources to any specific approach.

For small systems and simple missions either way may prove satisfactory, and indeed, the first approach can be the superior one if the system designer has a proven record of successes. On the other hand, painful experience on major systems has shown that as system and mission complexity increases, a point is reached beyond which the seat-of-the-pants approach simply invites economic and technical disaster.

It is not surprising therefore that the WSEIAC, in its recommendations, strongly favors the second approach. In particular, emphasis is placed upon methods which rely heavily upon an analytical "model" program. In WSEIAC usage, a model is any device, technique or process by means of which the specific relationships of a set of quantifiable system characteristics may be investigated. For example, the use of physical scale models in marine and aeronautical system design and development is a well established and sound practice. No designer of ships and aircraft would dream of constructing a prototype (let alone entering production) until he has tested his ideas in a tow tank or wind tunnel.

In the past, the ultimate user has continued this process of testing and evaluation by subjecting the complete system to special "shakedown" tests such as "war games;" that is, he has simulated the ultimate mission in as realistic a manner as possible without actually expending the system. He has "modeled" a tactical situation.

In more recent years, as mission complexity has increased, certain difficulties have arisen which make this logical sequence of events not wholly satisfactory. First, the use of scale models implies that the range of acceptable performance requirements is well established at the outset of the program, and it is only necessary to cut and try, with the aid of scale models, to meet them. The difficulty here is that it is not at all evident, for a complex mission, just what an acceptable range of requirements should be, particularly if some of those requirements must be stated in probabilistic terms.

Second, performance of full scale system tests under realistic conditions is becoming impractical for several reasons, not the least of which is the increasing cost of testing. In the case of weapon systems and certain space projects one may add safety, national prestige, political considerations (such as nuclear ban treaties) and the "one shot" nature of many missions as additional constraints on testing. Because of these several factors, final commitment of an unproven system to a mission is an increasingly frequent occurrence.

A potential solution to these difficulties is the judicious use of analytic modeling techniques to aid both in establishing subsystem requirements before development commences, and to compute the odds for mission success from less than full system test data.

In effect then, one is forced into the position of performing an analytic modeling program by default. Adequate system design cannot be accomplished in any other way.

From the preceding considerations, the general role of analytic modeling is clear. Analytic models provide insight. They make an empirical approach to system design economically feasible. They are a practical method of circumventing a variety of exterior constraints.

In addition, analytic models bring to bear an applicable body of theorems on stability, asymptotic behavior, and dynamic performance.

We have a right, then, to expect certain kinds of output from a modeling program. Clearly a modeling program should:

- aid in establishing requirements,
- provide an assessment of the odds for successful mission completion,
- isolate problems to gross areas,
- rank problems in their relative seriousness of impact on the mission, and
- provide a rational basis for evaluating and selecting between proposed system configurations and proposed solutions of discovered problems.

Clearly these outputs can be realized only if the scope of the modeling effort is adequate and only then when it is supported by a reasonable data base. Furthermore, these outputs are achievable only when the words, "system effectiveness" convey a definite meaning of sufficient scope.

The concept of system effectiveness has been expressed many times in many ways by many people. Sometimes one characteristic, such as reliability, has been emphasized as a major contributor to system effectiveness. At other times, other characteristics have been singled out for special attention.

The time has come to concentrate attention on the primary concern of management -- the over-all effectiveness of a system -- and to derive a way to predict and measure this over-all effectiveness and to put each contributing characteristic in its proper perspective within the over-all measure.

#### A. PRINCIPAL FACTORS OF EFFECTIVENESS

The WSEIAC has taken the position that system effectiveness is a quantitative measure of the extent to which a system may be expected to achieve a set of specific mission requirements. It is expressed as a function of three major system attributes:

- availability (A)
- dependability (D)
- capability (C).

Availability (A) is a measure of the condition of the system at the start of a mission, when the mission is called for at an unknown (random) point in time.

Dependability (D) is a measure of the system condition during the performance of the mission; given its condition (availability) at the start of the mission.

Capability (C) is a measure of the results of the mission; given the condition of the system during the mission (dependability).

Cost-effectiveness is the value received (effectiveness) for the resources expended (cost).

You will note that the WSEIAC has chosen a concept and definition of effectiveness based only on quantifiable factors. There are certain aspects of the problem of effectiveness, and an effective military posture, which are purely psychological. An effective military posture is one which deters the enemy; or given that this does not occur, will abbreviate the conflict in favor of our national interest.

A well publicized threat of missile retaliation, backed in actuality by only a cleverly concealed squadron of "wooden missiles," might deter the enemy and satisfy the first half of the above requirement; but "wooden missiles" would not satisfy the second half of the requirement. However, it is difficult, if not impossible, to quantify or assess the worth or value of deterrence. It must be left to military judgment. Thus, the WSEIAC concept makes no attempt to quantify these psychological factors. However, Section VII, Volume II of Task Group IV's report, "Risk and Uncertainty in Cost-Effectiveness," discusses the differences between quantifiable factors (which are called risks) and non-quantifiable factors (called uncertainties).<sup>(7)</sup> Risk is akin to rolling dice or playing roulette. The outcomes are, on the average, quantifiable and predictable. Uncertainty is synonymous with lack of information or inability to predict the outcome of the future; for example, the inability to prognosticate future weapon system configuration changes, either due to changes in hardware, operational concepts, or force size, and their consequent effect on costs. Uncertainty is a major factor in cost overruns.

Thus, even though the WSEIAC definition is based only on quantifiable factors, the differences between risk and uncertainty and between quantifiable and non-quantifiable (such as psychological) factors were recognized. Using these concepts as a fundamental point of reference, current engineering and management practices were examined.

#### B. EFFECTIVENESS/COST-EFFECTIVENESS TASK DESCRIPTIONS

In evaluating the work of the task groups, a logical framework for conducting System/Cost-Effectiveness Prediction and Analysis has evolved. It is reflected in the systematic fifteen step procedure shown in Figure 1 (fold-out on page 21. It will be helpful to fold the figure out and refer to it now. This flow diagram is a composite representation that reflects the consensus of the five WSEIAC Task Groups. It illustrates the sequence (and the order) of the essential tasks that must be performed in conducting a system effectiveness/cost-effectiveness prediction/evaluation/augmentation cycle in the Conceptual, Definition, Acquisition and Operational Phases; i.e., to evaluate (or predict) the degree of effectiveness that has (or will) be attained for any achieved (or proposed) system configuration and to augment it as required.

The choice of the word "prediction" is not accidental. It is impossible to measure effectiveness short of total war; hence, effectiveness calculations always contain an element of prediction. The object of these predictions is two fold:

- System effectiveness predictions form a basis for judging the adequacy of our defense posture.
- Cost-effectiveness predictions form a rational basis for management decisions.

Efficient use of such predictions will provide a technical key to more effective selection, definition, development, control, evaluation and support of a system. It will also provide a basis for more enlightened program management.

A complete cycle is defined by fifteen essential steps commencing with a mission definition and terminating with a change analysis. Twelve of

these steps specifically define effectiveness and cost-prediction activities; the remaining three define management, system, and change analysis activities.

Since a large portion of the output of the WSEIAC is devoted to presenting and illustrating the use of these steps and techniques for effectiveness/cost-effectiveness prediction, Appendix I has been added to discuss each step in considerable detail, including the WSEIAC recommendations for implementation of each step.

These steps logically fit into and enhance the AFSC 375 series manuals which are an expression of current Air Force program management philosophy for the system life-cycle. The activity networks for each phase of the system life-cycle shown in these AFSC 375 series manuals contain fundamental program planning and surveillance elements. The output of the WSEIAC forms an integral part of system management. Thus, to implement the WSEIAC's recommended techniques, the activity networks of the AFSC 375 series of manuals must be revised to include system effectiveness critical activities.

It should be carefully noted that the fifteen steps of Figure 1 are intended to be repeated since the prediction of effectiveness/cost-effectiveness is not a once-only affair; it is cyclic.

- In the Conceptual and Definition Phases, it is a repetitive comparison of pairs of alternative solutions to a problem.
- During the Acquisition Phase, it is an iterated comparison of current status with requirements, to be used as a management guide in the allocation of resources.
- During the Operational Phase, it is both a periodic monitor of current capability and a tool for evaluation of system improvements.

In spite of the different uses cited, effectiveness and cost-effectiveness predictions may be conducted by a similar set of steps in each phase of the system life-cycle. The next section explains in more detail how the predictions and the WSEIAC's findings relate to each phase; here we shall only briefly indicate the nature of each block of Figure 1. For further detail, see Appendix I.

## BLOCK 1.0 MISSION DEFINITION

It is a fundamental requirement of the methods recommended by the WSEIAC that a clear and unambiguous statement of the mission of a system be obtained. This definition should contain:

- a description of the purpose of the system, and
- system quantitative requirements.

## BLOCK 2.0 RESOURCES

Resources usually evidence themselves as a practical constraint on the development and procurement of a system. There are four principal areas of consideration here:

- budget
- personnel resources
- industry capacity
- technological factors.

An example of the way in which technical factors are specifically accounted for is given in the example contained in Appendix II to Volume II of the Task Group IV Final Report.<sup>(7)</sup>

## BLOCK 3.0 SYSTEM DESCRIPTION

System description consists of either:

- (1) identification of alternative system configurations, or
- (2) configuration documentation

followed by

- (3) a system summary description.

During the Conceptual Phase, steps (1) and (3) form a logical sequence. In the late Definition Phase and Acquisition Phase, the emphasis will increasingly shift to steps (2) and (3).

The object of the last step is to present an uncluttered picture of only those features of the system structure which have a direct bearing on:

- the estimation of system effectiveness, or
- a cost-effectiveness trade-off study.

#### BLOCK 4.0     FIGURES OF MERIT

A figure of merit is a statement which relates mission (or program) objectives to quantitative system requirements. It is a statement of the ability of a system to meet an operational need, including the recognition of the risk and uncertainty that are fundamental characteristics of the military mission.

The most comprehensive figures of merit have been dubbed system effectiveness and cost-effectiveness. System effectiveness is a quantitative measure of the extent to which a system may be expected to achieve a set of specific mission requirements. It is regarded to be a function of:

- availability,
- dependability,
- capability.

Cost-effectiveness is a measure of the value received (effectiveness) for the resources expended (cost).

#### BLOCK 5.0     SPECIFICATION OF ACCOUNTABLE FACTORS

As a preliminary to model construction and following mission definition, system description, and specification of figures of merit, it is necessary to spell out the boundary conditions of the analysis to be conducted. First, the level of accountability must be specified:

- What are the system interfaces?
- What is the depth of the analysis?
- What are the variables of the analysis?

Second, it is necessary to define constraints on:

- data,
- schedule,
- burden,
- resources,
- acceptable risk and uncertainty,
- physical environment.

In addition, it is necessary to spell out the accountable factors in the areas of

- personnel,

- procedures,
- hardware,
- logistics.

#### BLOCK 6.0 IDENTIFY DATA SOURCES

The detailed structure of a model must be tailored to fit the type of data available. This is, of course, a two way road: only those questions may be answered for which data exists. Early identification of data sources will permit an investigation of the limitations of the expected data sources and will alert management to the necessity of planning to acquire supplementary data.

#### BLOCK 7.0 MODEL CONSTRUCTION

Model construction is a four step process:

- list assumptions,
- list variables and define model parameters,
- construct effectiveness model(s),
- construct cost model(s).

The listing of assumptions is crucial. The usefulness of a model can be severely restricted if the assumptions violate reality. A clear statement of assumptions is, therefore, a necessity in judging the validity of the results of a model exercise.

Listing variables and defining the model parameters permits a comparison of the structure of the model with the list of accountable factors. It provides a means of judging the completeness of the model structure.

Effectiveness models should reflect the three major system attributes;

- availability,
- dependability,
- capability.

Task Group II has given several explicit illustrations of modeling these factors for Air Force systems in Volume II and Volume III of their final report.<sup>(3,4)</sup> It should be recognized that, although all but one of the illustrations are "pencil and paper" models, the complexities of a large system may very well require that the actual model exercise be conducted on a computer.

Task Group IV presents several examples of cost-effectiveness model construction in Volume II and Volume III of their final report.<sup>(7, 8)</sup>

#### BLOCK 8.0 DATA ACQUISITION

Planning for data acquisition requires careful attention to:

- specification of data elements
- specification of test methodology
- specification of a data collection system.

The key to an adequate data acquisition program is the determination of those system events which are significant. A system event is only of significance if it contributes to the evaluation of a parameter of the system model. Data elements are only significant if they uniquely locate the system event in space and time with respect to other system events.

Frequently it is necessary to answer questions which call for special testing. Maximum utilization of the acquired data can be achieved only if the specification of test methodology is accomplished in a manner responsive to the needs of the system model. During model construction any special testing that may be required should be communicated to those responsible for planning for data collection.

In the Air Force, specification of a data collection system requires a consideration of "data" in a broader sense than its use in "data element" above. A data collection system is the organized process used to gather, store, retrieve, display, publish, and distribute a wide spectrum of system-related information including, for example, training manuals, program plans, management summaries, cost data, performance data, etc.

#### BLOCK 9.0 DATA PROCESSING

The processing of data for most Air Force systems is a large undertaking requiring careful attention to:

- parameter estimation methods
- administrative organization
- personnel selection and training
- software development
- hardware specification (computing facilities).

The specification of parameter estimation methods is a crucial step. The scope of data processing is so large that it is unreasonable to assume that those who process data are aware of all the ramifications of their work. Accordingly, great care should be exercised in:

- specification of effectiveness parameter estimation methods, and
- specification of cost estimating relationships.

Techniques in these latter two areas are discussed by Task Group II and Task Group IV.<sup>(3, 4, 7, 8)</sup> The former areas are treated in detail by Task Group III.<sup>(5)</sup> This latter task group, in recognition of the complexity of the data acquisition and data processing tasks, has recommended the establishment of a System Information Bank (SIB) for each Air Force system and a System Effectiveness Information Central (SEIC) as a focal point for system effectiveness information retention on an Air Force wide basis.

#### BLOCK 10.0 SPECIFY SCHEDULE

Schedule is viewed as a constraint. It is assumed that schedule control will be maintained by some form of PERT. In addition, schedule should be accounted for (possibly implicitly) in the system effectiveness/cost-effectiveness models.

#### BLOCK 11.0 MODEL EXERCISE

There are two principal uses of models:

- evaluation of current status,
- prediction of potential status.

Evaluation provides:

- surveillance of current system status against quantitative system requirements,
- feedback upon the efficacy of the management decision process,
- a means of determining system weaknesses or potential problem areas,

- a point estimate of system effectiveness which includes all relevant factors within one conceptual framework.

Prediction provides decision aids through comparative (cost-effective) analysis of competing:

- system configurations, and
- problem solutions.

The use of a system model involves eight steps:

- perform checks on model,
- calculate FOM's,
- do trade-offs within constraints,
- compare calculations with standard of reference,
- calculate effect of risk,
- calculate effect of uncertainty,
- calculate parameter sensitivity curves, and
- interpret runs.

A model exercise is the rational basis for optimization within constraints.

#### **BLOCK 12.0 PREPARE MANAGEMENT SUMMARY REPORTS**

The purpose of a management summary report is to communicate the results of a model exercise to those who are responsible for making decisions. Hence, it must be executed in a manner that aids the decision process. The management summary report must contain not only the main results of the model exercise in a format that is readily understood, but in addition it should contain:

- system quantitative requirements,
- current system status,
- resources (remaining),
- trends,
- optimum (re)allocation of resources, and
- risk and uncertainty qualifications.

### BLOCK 13.0 DECISION PROCESS

Implementation of the WSEIAC recommendations will have an impact upon the decision process. Formal effectiveness/cost-effectiveness prediction of the scope envisioned by the WSEIAC is without precedent. Decision processes will tend to become more formalized and prescribed. The use of formal decision algorithms will become more widespread. This does not mean that the management decision process has been relegated to a witless computer. It does mean that management will have a new wealth of correlated facts at beck and call, and the decision process will become easier and more accurate in many instances. Nevertheless, the ultimate act of decision must rest with a human who can account for the qualitative aspects of the world, those psychological and political intangibles that the formalized trade studies do not encompass.

### BLOCK 14.0 IMPLEMENT DECISION

It should be carefully noted that the steps of the task analysis under discussion apply in any and all phases of a system life-cycle. Accordingly, implementation of a decision will tend to differ from phase to phase. In the Conceptual Phase the decision may take any of the following forms:

- further studies,
- initiation of research,
- initiation of exploratory development,
- revision of an existing SOR, or
- initiation of a TSOR.

In the Definition and later phases, decision implementation tends to become more constrained. For typical uses of the WSEIAC output by phase see Section IV.

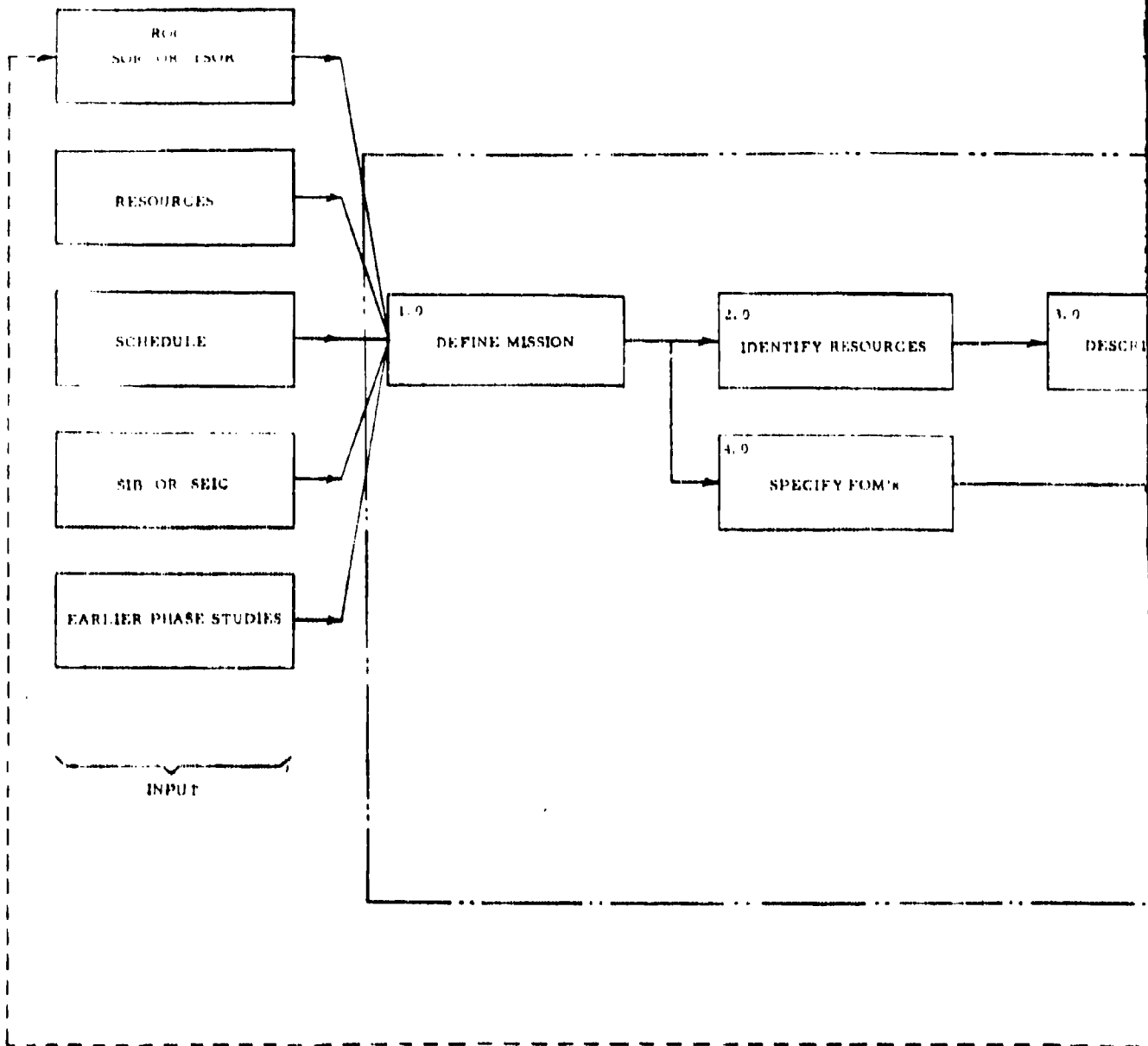
### BLOCK 15.0 CHANGE ANALYSIS

The implementation of a decision based upon effectiveness/cost-effectiveness considerations generally implies a change in one or more of the following areas:

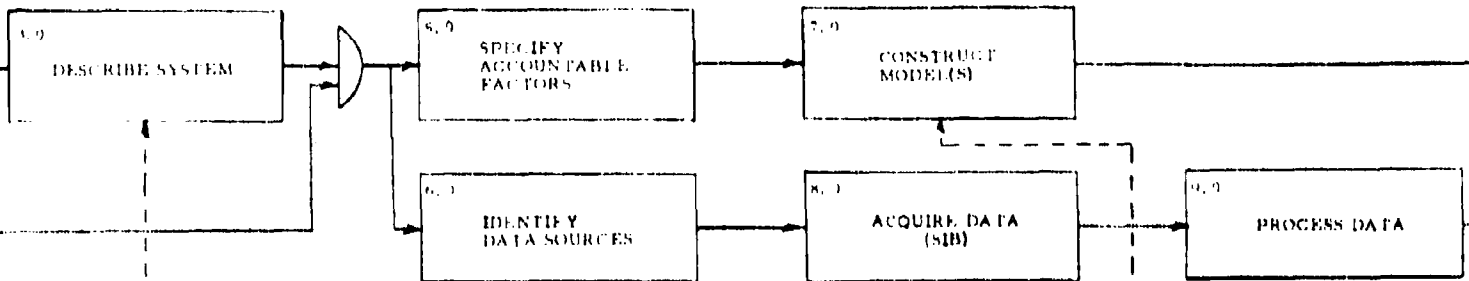
- schedule,
- model(s),
- system, or
- requirements.

Each iteration of the effectiveness/cost-effectiveness prediction/evaluation/augmentation cycle should be accompanied by a change analysis against these areas. The result of this activity will be a monitoring of the net effect of each decision and the accomplishment of program surveillance.

We have briefly indicated the nature of each task in Figure 1. We shall now turn to a brief discussion of the uses of the WSEIAC output by phase of a system life-cycle.



EFFECTIVENESS/COST-EFFECTIVENESS PREDICTION



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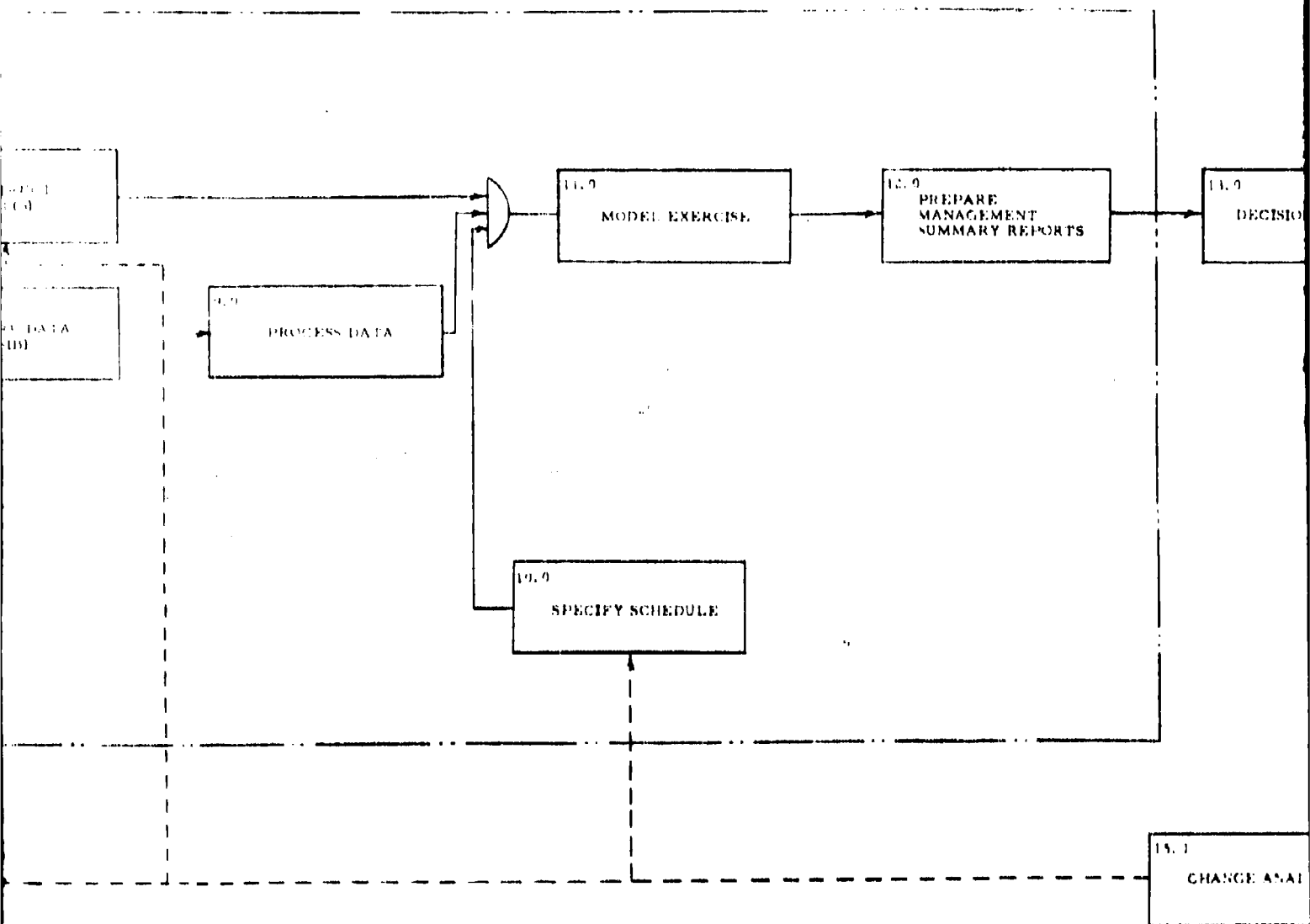


FIGURE 1

EXPANDED ACTIVITY  
EFFECTIVENESS PREDICTION  
CYCLE - CONCEPTUAL  
OPERATIONAL PHASES

3

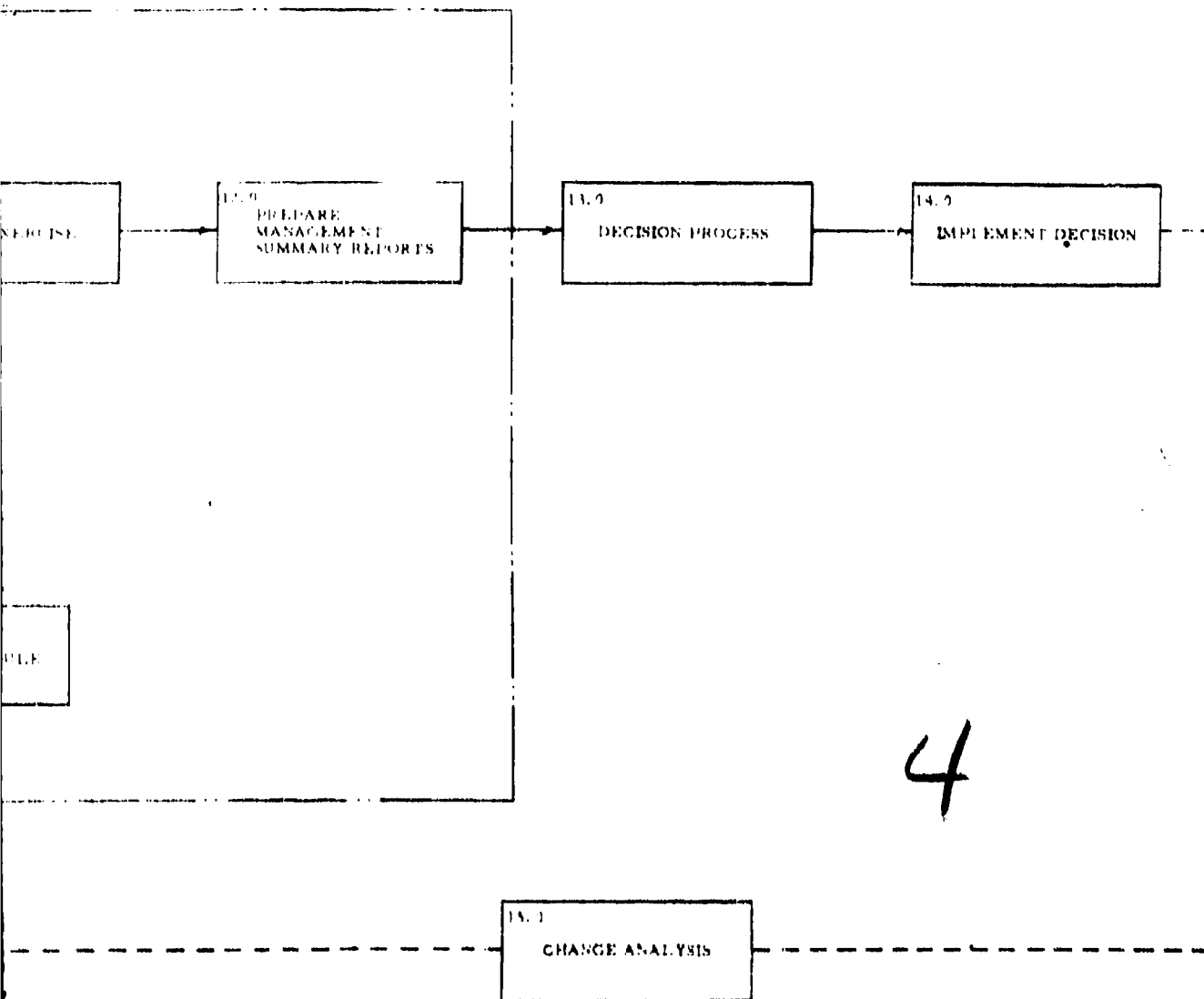
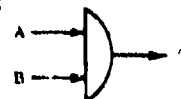


FIGURE 1

NOTE



Symbol denotes that events A and B must occur before event C can occur.

EXPANDED ACTIVITY NETWORK OF THE STEPS IN A SYSTEM EFFECTIVENESS PREDICTION/EVALUATION/AUGMENTATION CYCLE - CONCEPTUAL, DEFINITION, ACQUISITION AND OPERATIONAL PHASES

## SECTION IV

### USE OF WSEIAC OUTPUT BY PHASE OF SYSTEM LIFE-CYCLE

This Section presents a general roadmap illustrating the role of cost-effectiveness prediction techniques in each phase of the system life-cycle as defined in the AFSC 375 series of manuals.

#### A. CONCEPTUAL PHASE

The system life cycle is initiated by a statement of a general need for a particular operational capability. The general objective of this phase is to establish a feasible technical approach for satisfying the general requirement, to evaluate whether a specific approach is worth pursuing, or whether the military requirement should be satisfied in another manner. The phase extends from determination of a broad objective or need, to Air Force approval of the Program Change Proposal covering the Definition Phase.

The Conceptual Phase studies are intended to serve a twofold purpose:

- provide explicit and unambiguous definitions of system effectiveness for the particular system to which the Tentative Specific Operational Requirement (TSOR) applies;
- provide guidelines for system refinement in the Definition Phase.

The WSEIAC has recommended that the process of documenting a TSOR or SOR be formalized. Toward that end they have proposed an Air Force manual for the preparation of an SOR based on the current Headquarters Instruction, HOI-DORQ 11-7.<sup>(1)</sup>

In order to insure that the requirements of the SOR are met, the WSEIAC has further proposed an AFR calling for:

- the pursuit of a system effectiveness program throughout the life-cycle of a system,
- the establishment of a System Information Bank (SIB) for each system during the Conceptual Phase, and

- the inclusion of Conceptual Phase studies in the TSOR or SOR (by reference).

Drafts of the proposed manual and regulation are included in the final report of Task Group I.<sup>(1)</sup>

The WSEIAC also recommends that quantitative system requirements should not be made absolute and firm in the Conceptual Phase. The output of the Conceptual Phase should be a tentative SOR (TSOR). Only those requirements which can be fully substantiated as being absolutely the minimum acceptable should be made firm and irrevocable. Keeping the requirements as flexible as possible permits better trade-offs in later phases. Figure 2 shows a simplified activity network for establishing system effectiveness requirements in the Conceptual Phase.

#### B. DEFINITION PHASE

The purpose of the Definition Phase is to refine the definition of the system to the subsystem level based on the guidelines established in the TSOR and by the Conceptual Phase studies.

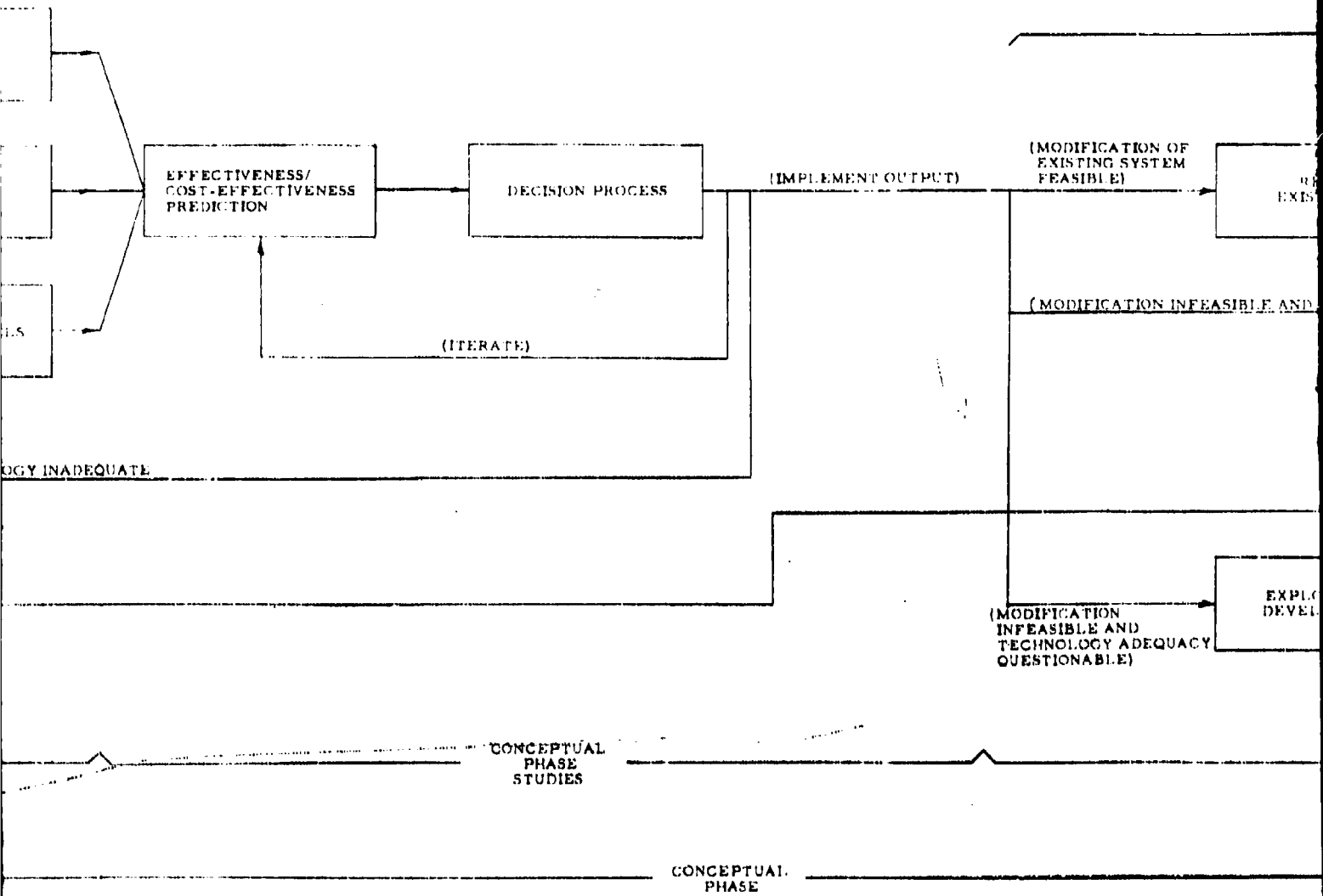
With respect to the simplified activity network of Figure 3, the inputs to this phase are:

- definition of resources;
- definition of scenario;
- definition of schedule (time scale);
- advanced development data;
- TSOR containing:
  - definition of effectiveness,
  - preliminary quantitative requirements,
  - definition of primitive system; and
- Conceptual Phase studies.

The recommended method of refinement of the primitive system configuration developed in the Conceptual Phase is the iterated performance of the following sequence of steps:

- define potential cost-effectiveness improvement (change) to primitive system;





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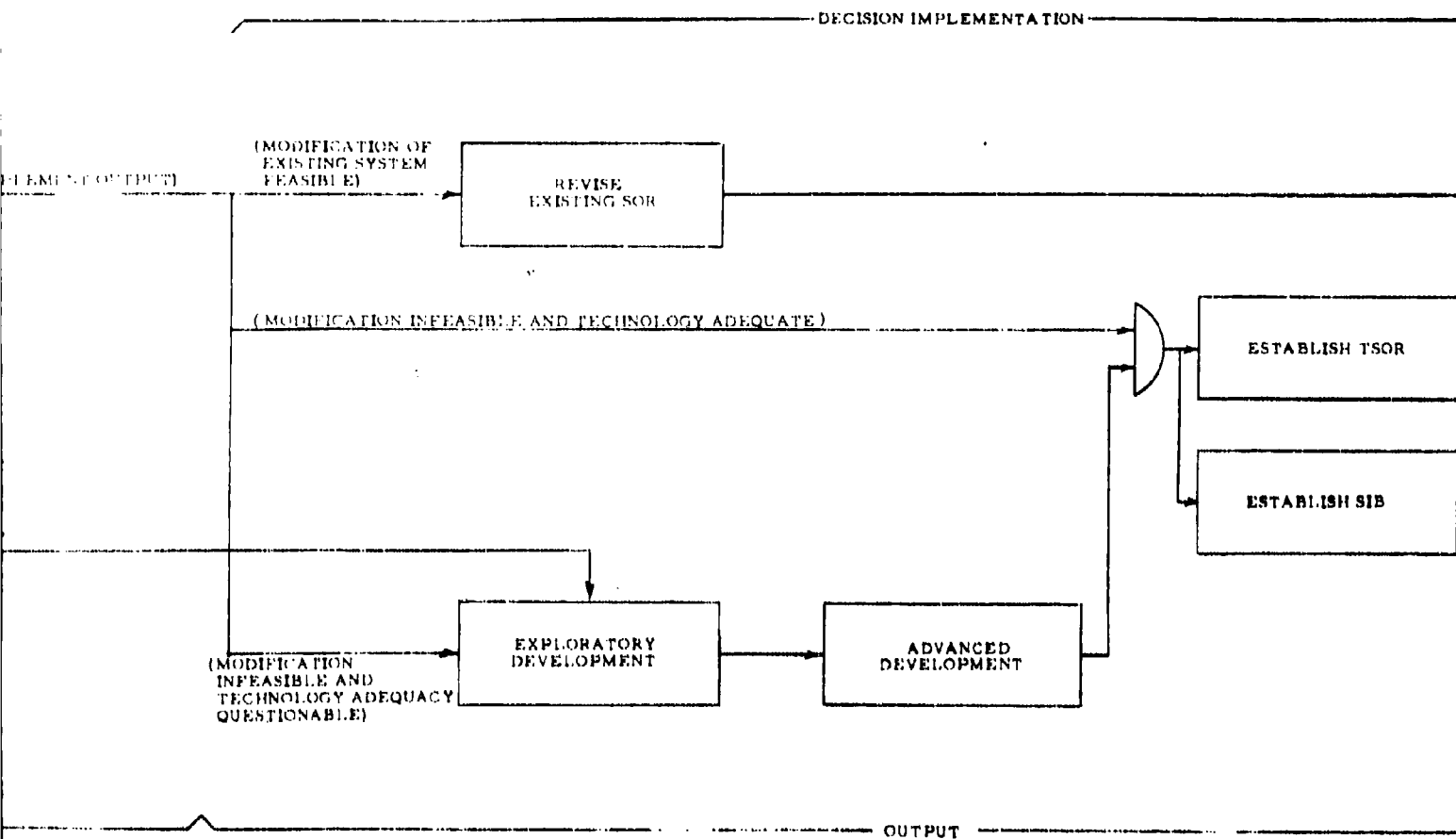


FIGURE 2 - SIM  
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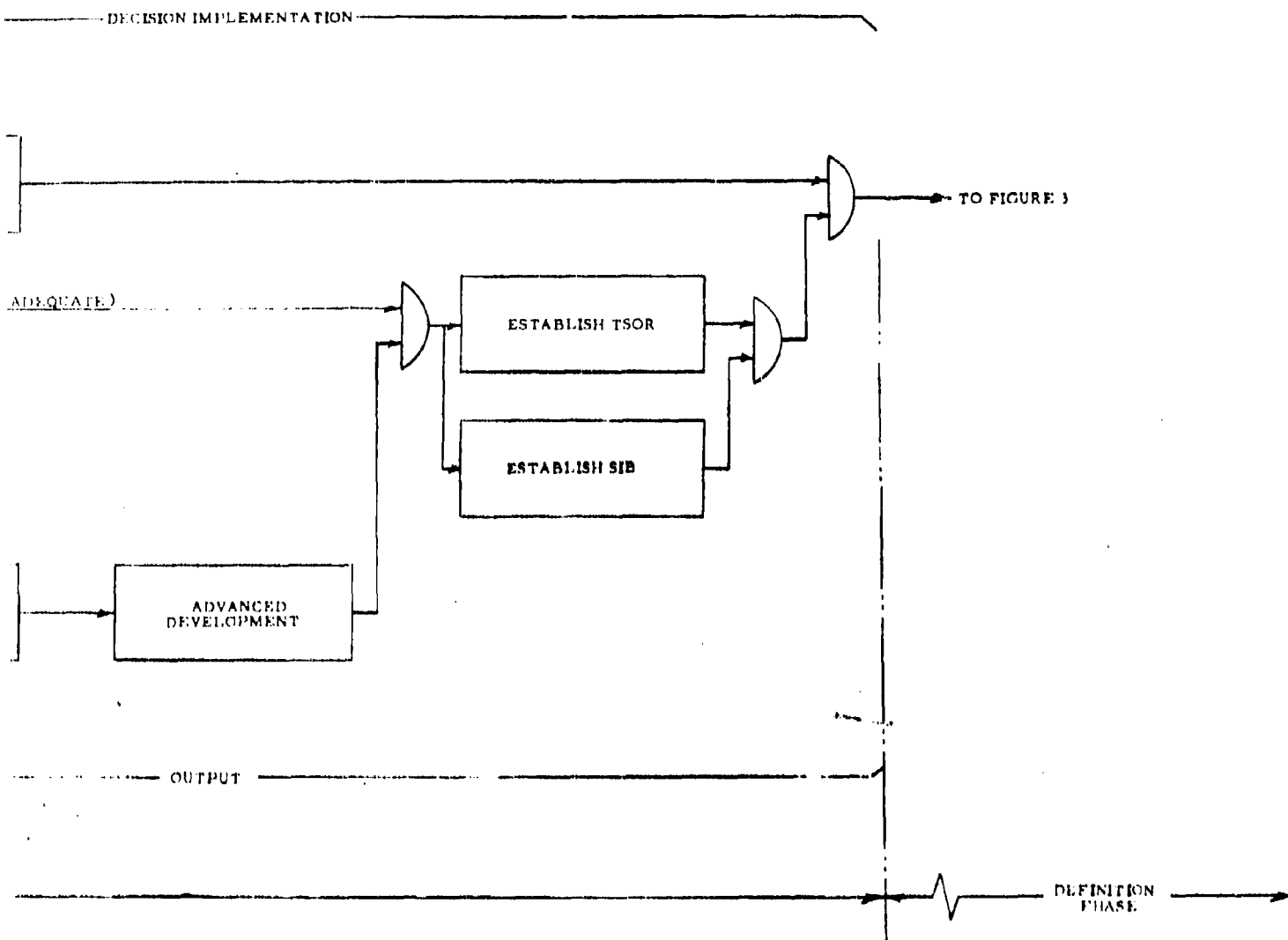
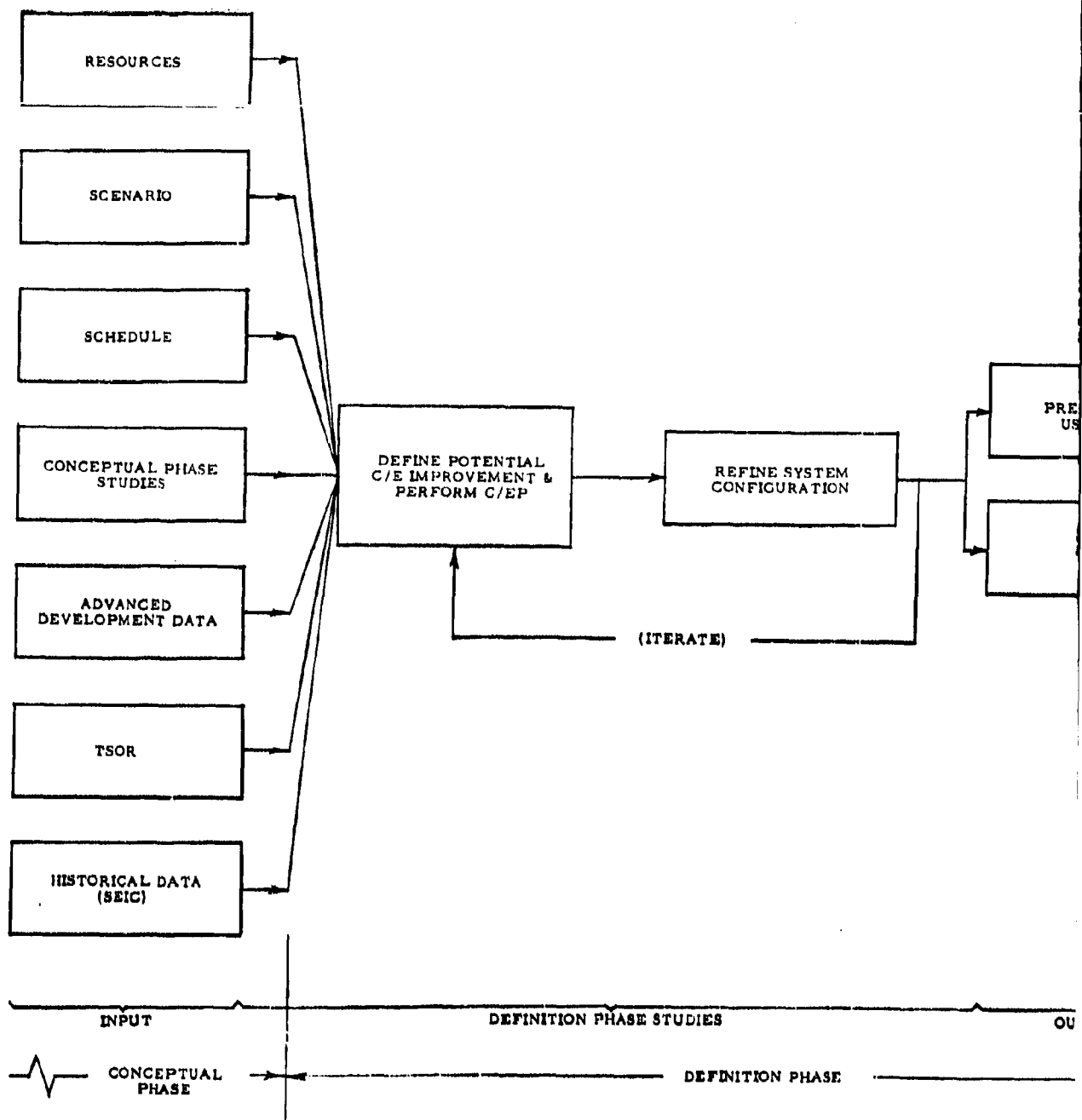


FIGURE 2 - SIMPLIFIED ACTIVITY NETWORK FOR  
ESTABLISHING SYSTEM EFFECTIVENESS  
REQUIREMENTS IN THE CONCEPTUAL PHASE

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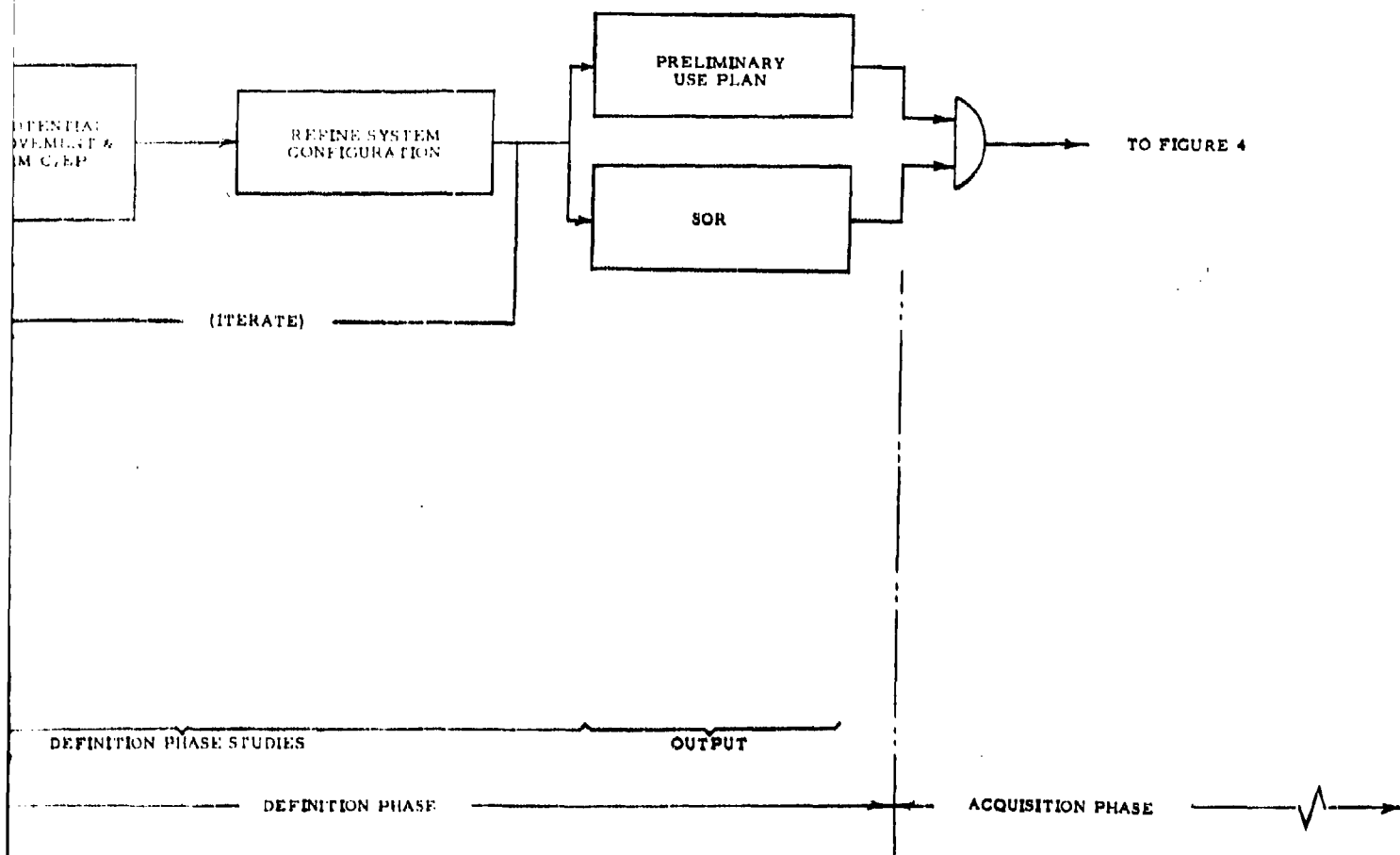


FIGURE 3  
SIMPLIFIED ACTIVITY NETWORK FOR SYSTEM DEFINITION

refine functional description of system to reflect potential change;

- perform a cost-effectiveness prediction based on historical (generic) data and/or advanced development data;
- refine system configuration by relative cost-effectiveness ranking of alternative improvements;
- iterate steps as required.

The output of the Definition Phase is a preliminary use plan and a firm SOR containing at least the following:

- the definition of system effectiveness;
- minimum acceptable quantitative system requirements;
- documented Conceptual and Definition Phase studies (by reference).

Additional essential outputs are:

- subsystem performance specifications;
- cost and schedule estimates.

The Definition Phase is initiated by a System Definition Directive, and ends with issuance of a System Program Directive.

#### C. ACQUISITION PHASE

The purpose of the Acquisition Phase is to develop and produce the system based upon a firm SOR.

The WSEIAC recommends that during this phase, cost-effectiveness techniques be used as a management aid in:

- status monitoring of system development against the quantitative requirements of the SOR;
- allocation of resources.

The sequence of steps which must be performed to provide the relation among these factors is called system cost-effectiveness prediction.

This relationship is illustrated in Figure 4, which specifically indicates that system effectiveness/cost-effectiveness prediction is the focal point which provides management perspective as to the relationship between system status, available resources, constraints, and system requirements.

This phase starts after issuance of the System Program Directive and ends with acceptance by the user of the last operating unit in a certain series, or until the SOR has been demonstrated through Category II testing and all required updating changes resulting from the testing have been identified, approved, and placed on procurement, whichever occurs later.

#### D. OPERATIONAL PHASE

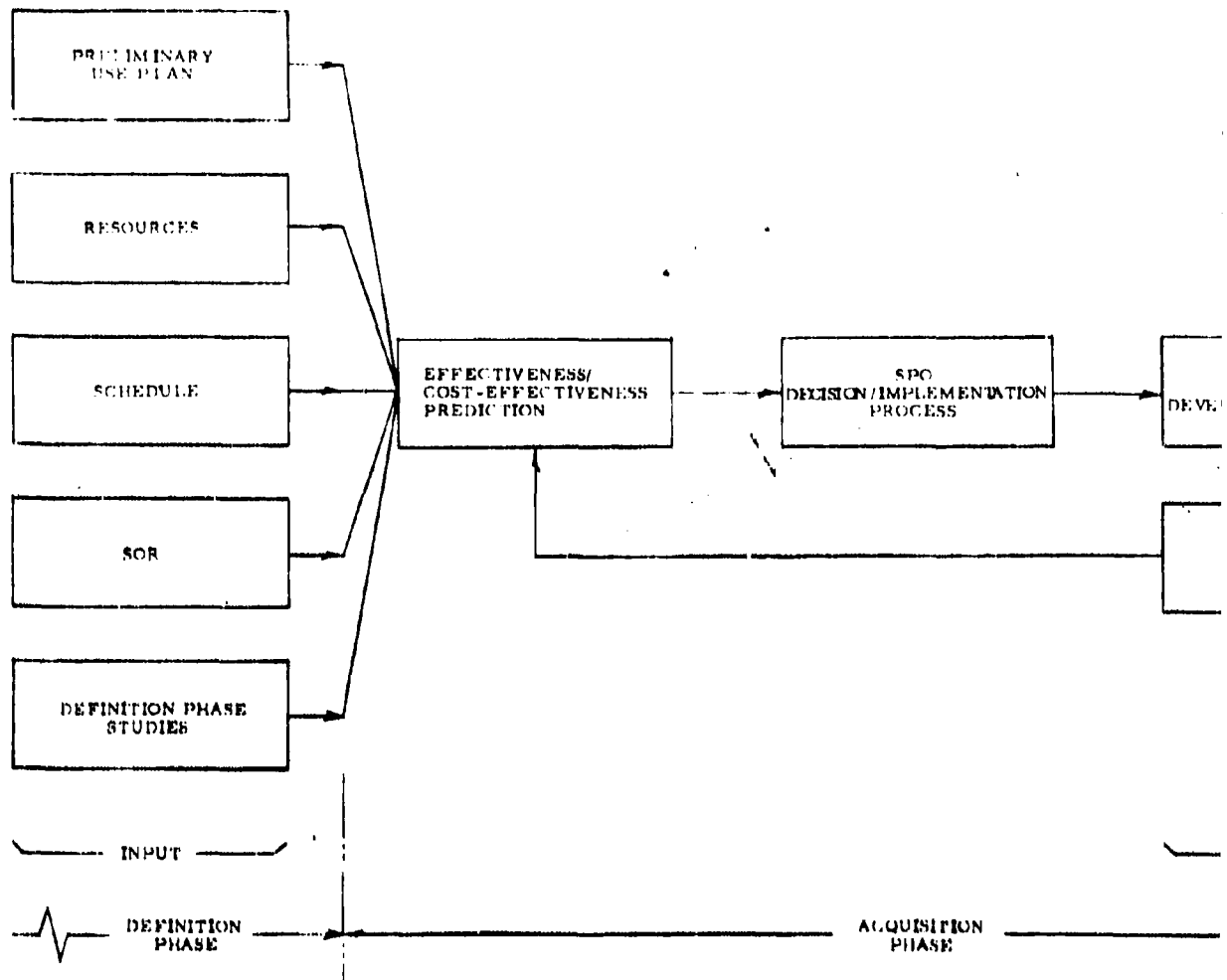
The Operational Phase is identified as the period of system use (and field support). During this phase of system life, the techniques recommended by the WSEIAC will:

- aid the using command in performing a critical evaluation of the system;
- aid the support command in achieving an economical and timely support of the system by verifying the earlier determined provisioning and in evaluating proposed modifications.

Figure 5 indicates the relationship between system effectiveness/cost-effectiveness prediction, the System Information Bank (SIB), the using/support management, and system activities.

As in the Acquisition Phase, system effectiveness/cost-effectiveness prediction is the focal point which provides management perspective.

This phase begins with acceptance by the user of the first operating unit, continues until final disposition of the system.



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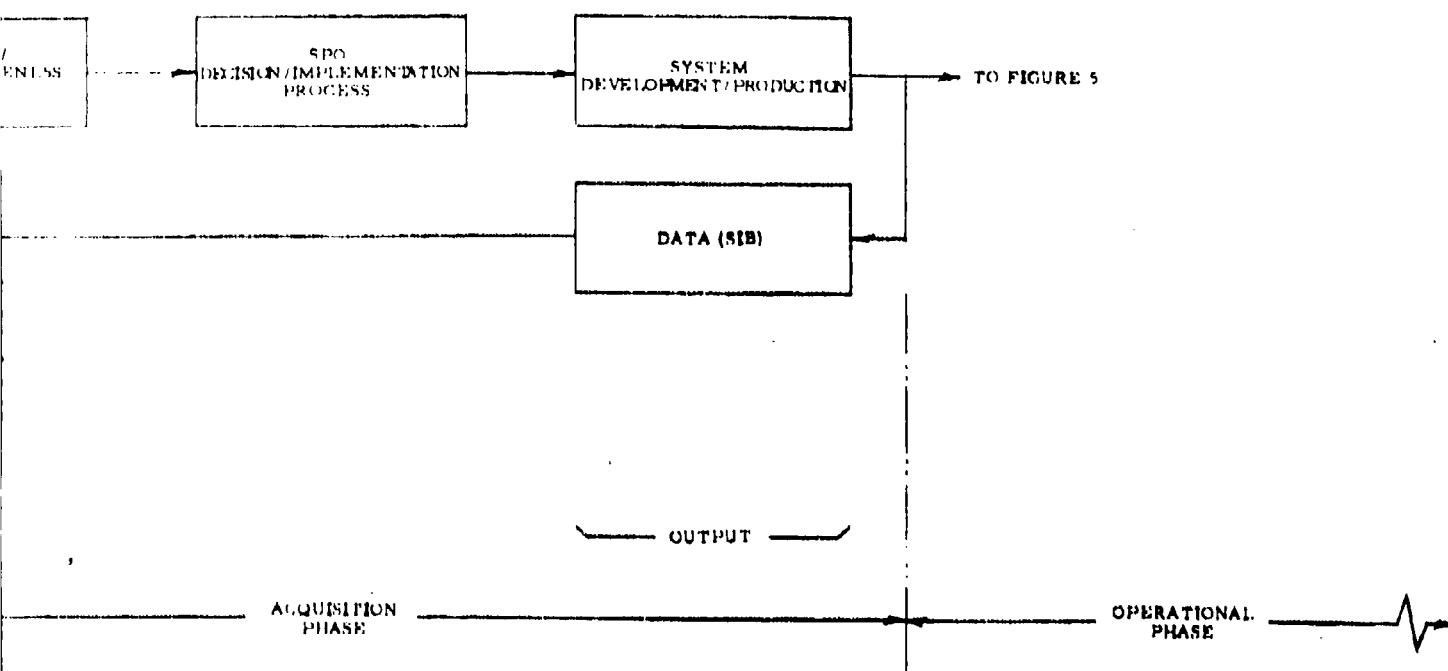


FIGURE 4

SIMPLIFIED ACTIVITY NETWORK FOR SYSTEM REFINEMENT  
AND STATUS MONITORING DURING THE ACQUISITION PHASE

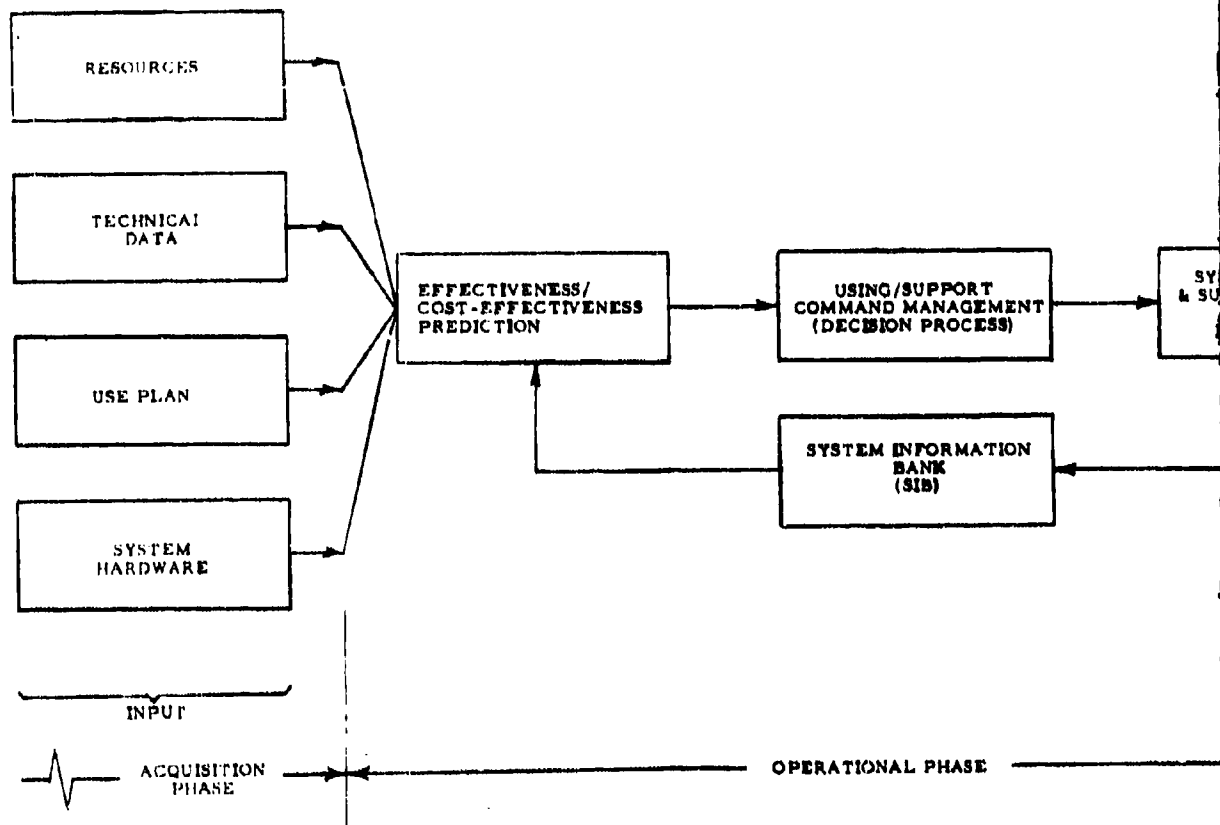
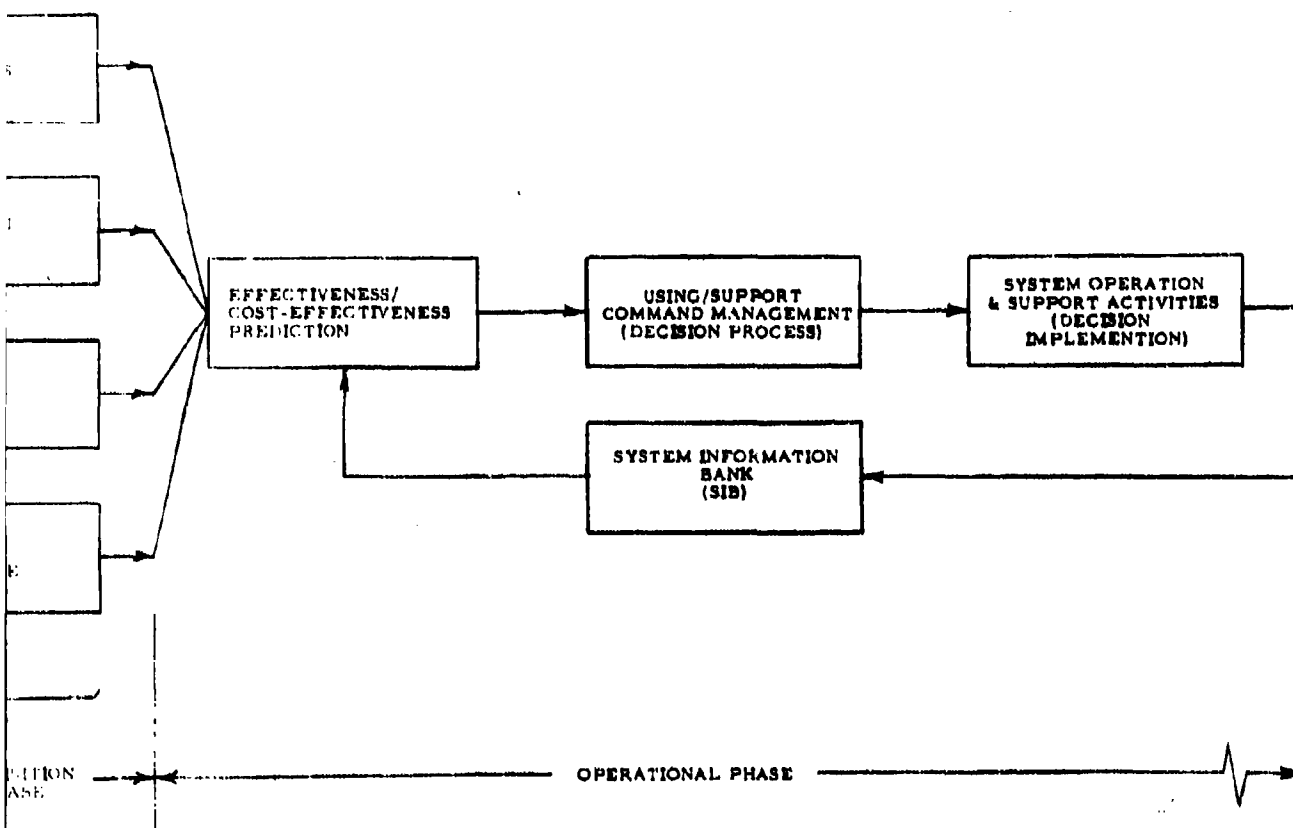


FIGURE 5  
SIMPLIFIED ACTIVITY NETWORK  
EVALUATION AND SUPPORT DURING



2

FIGURE 5  
SIMPLIFIED ACTIVITY NETWORK FOR OPERATIONAL  
EVALUATION AND SUPPORT DURING OPERATIONAL PHASE

/

SECTION V  
EFFECTIVENESS ASSURANCE MANAGEMENT

A. INTRODUCTION

System effectiveness has two major aspects. The first is to provide a quantitative basis for establishing requirements during project inception and definition and for evaluating achievements during acquisition and operation. The second is to provide management disciplines that will allow achievement of the predicted optimum levels of system effectiveness. To do so requires resources development for each activity that is critical to system effectiveness and development of program management methods to assure effective application of these resources.

It is not enough to predict what could be achieved by good engineering, good manufacturing and good management and to be able to measure later achievements. It is necessary to develop and apply techniques that will assure that engineering, manufacturing and management are performed in a way that will realize the potential system effectiveness. The Air Force has provided the basis for such assurance through program management technology in accordance with the AF 375 series of documents. Unfortunately, these documents do not yet clearly identify all the steps that must be taken to provide system effectiveness assurance; neither do they deal with resources development in the form of the technology and people trained and motivated specifically in system effectiveness techniques.

B. THE MANAGEMENT CONCEPT

Task Group V has identified six major segments of management inherent in the development and application of resources toward achievement of system effectiveness. These segments fall into two groups. The first, Resource Development (Experience Retention), includes:

- Data Acquisition
- Techniques Development
- Personnel Development.

The second group, Resource Application (Program Management), includes:

- Program Planning
- Input Surveillance
- Output Evaluation.

The recognition and disciplined treatment of activities critical to effectiveness included within each of these six segments constitute the management concept. Critical activities are those activities that experience has shown must be subjected to formal discipline in order to assure system effectiveness.

Within this concept, "discipline" is equated with all types of control over the activities of people. It consists of training, motivation, command, and audit. Application of these principles to specifically identified system effectiveness critical activities allows evaluation of current status and defines those areas where specific improvement can be introduced. For example, an Air Force program director may receive general training in program management philosophy but still be left in doubt about specific actions that he should take in managing a new program. By contrast, if he is taught that there is a tangible activity called "functional flow analysis," -- if he is provided with documented technology for this activity and motivated to apply it, -- if he is commanded by AFSCM 375-5 to require his contractors to schedule and fund the performance of this activity, -- and if the program is audited by his inspector general, there is a high probability that the activity will be accomplished.

### C. THE SIX SEGMENTS OF ASSURANCE MANAGEMENT

1. Data Acquisition In general, data acquisition systems are established to provide program directors with information for the management of the project from which the data is obtained. In fact, AFSC/AFLC 310-1 (Management of Contractor Data and Reports) restricts data acquisition to this purpose. For resources development purposes, it is necessary to develop data feedback into forms suitable for decision assurance on future projects. For example, data on the generic failure rates of electronic parts must be obtained from current projects and fed forward for use in predicting

the reliability of future systems. Resource development data requirements include engineering type data obtained by dissection and analysis of failed parts. However, information on management lessons learned in fields such as source selection, cost estimation, and manufacturing process control also must be acquired and fed back. Data requirements are shown as a portion of the input prior to Block 1.0 and in Blocks 6.0, 8.0 and 9.0 of Figure 1 (page 21).

2. Technology Development Many important techniques, such as electronic stress analysis, design review, or production environmental testing, start out by competent people actually performing them as required to support a particular project. Temporary technical excellence may be developed by such effort, but this is not enough. In order to assure repetition of successes and avoidance of repetition of failures, and in order to spread technical excellence throughout the industry, it is necessary to document the technology. Such documentation covers lessons learned on all projects and thereby represents the best of which industry is capable. Although the fifteen-step procedure outlined in Section III provides a step-by-step framework against which to perform an effectiveness/cost-effectiveness analysis, considerable development of the necessary techniques is needed. These are outlined in Section VI, "General Conclusions and Recommendations."

3. Personnel Development Documented technology does not of itself achieve results. People must be taught the technology and motivated to use it. Such people then constitute the primary resource for successful execution of new projects. Task Group V has identified training needs and called for additional programs within the Air University and the Air Training Command. Similar effort is required within industry.

4. Program Planning Each of the Air Force 375 series documents includes an activity network. These may be regarded as model program plans. They identify activities that must be required and funded by the System Program Office. In addition, they identify two types of output from these activities. The final output from decision making disciplines may be called "decision disclosure documents." For example, a specific operational

requirement is a disclosure of decisions made during the Conceptual Phase of a system life-cycle. These decision disclosure documents are like the baton in a relay race. They are the tangible item that is passed on from one group to the next or from one phase to the next. The second type of output may be called "decision guide data." Such data is generated by the activities as a basis for the decisions set forth in decision disclosure documents. For example, the activity known as "functional flow analysis" results in "functional flow block diagrams." This data is essential to assuring the quality of decisions made by the systems engineer, and these decisions are reflected in "end item detail specifications."

Although AF 375 series networks are, in fact, model program plans, actual plans are prepared in many forms. Some are narrative, some tabular, and some are combinations of these two basic forms. In all cases, program plans must show which system effectiveness critical activities are required and funded. In addition, they should show who is responsible for their execution, when they will be performed, what decision guide data will be generated, and which decision disclosure documents will be affected by this data.

5. Input Surveillance The ideal relationship between a buyer and a seller is one in which the interface is limited to the buyer specifying exactly what he wants and providing qualification tests and receiving inspection criteria to assure that he receives it. This type of relationship may be described by the term "output contracting." For this relationship to be satisfactory, it is essential that:

- the buyer can specify numerically every requirement for the product, including reliability and maintainability values;
- the buyer and seller can agree on a funded demonstration test that will prove that all numerical requirements have been met;
- the buyer can tolerate the schedule delay and extra cost that will result if the seller fails to pass a specified demonstration test.

Unfortunately, it is seldom possible to negotiate and fund an

adequate demonstration plan for reliability, maintainability, and all the other characteristics which contribute to system effectiveness. It is even more rare for a buyer to be in a position to tolerate the schedule slippage and extra cost that would occur if the contractor failed to meet specified requirements. Consequently, the Air Force has found it necessary to supplement output contracting by specifying that activities critical to program objectives will be performed by their contractors in accordance with disciplined procedures. This may be called "input contracting."

It follows that contract management practices have had to be extended to include surveillance over the accomplishment of critical activities. This surveillance may take the form of assignment of engineering development officers as Air Force plant representatives and as chairmen of technical-direction meetings at the contractor's plant. All of these practices may be described by the term "input surveillance."

6. Output Evaluation Program management technology predicts that if work statements and program plans are followed, certain results will be obtained. It is necessary to assure that actual results are as predicted, and, if they are not, to take rapid corrective action. The techniques for doing so may be described by the term "output evaluation." This segment of the system effectiveness assurance management system includes design reviews, qualification testing, receiving inspection, and Category I, II, and III system testing. It also includes failure analysis, feedback and corrective action by project personnel, and effectiveness/cost-effectiveness evaluation.

Figure 6 illustrates the relationship of the above six segments of effectiveness assurance management as a closed loop process. The left hand arrow illustrates that operational executives are responsible for obtaining resources from functional groups and applying them to each critical activity. The right hand arrow illustrates that functional executives must acquire and document the experience of present and past programs as an essential basis for new programs. Development of technical excellence for each critical activity in a form that can be transferred to new projects depends on this continuous feedback from current projects.

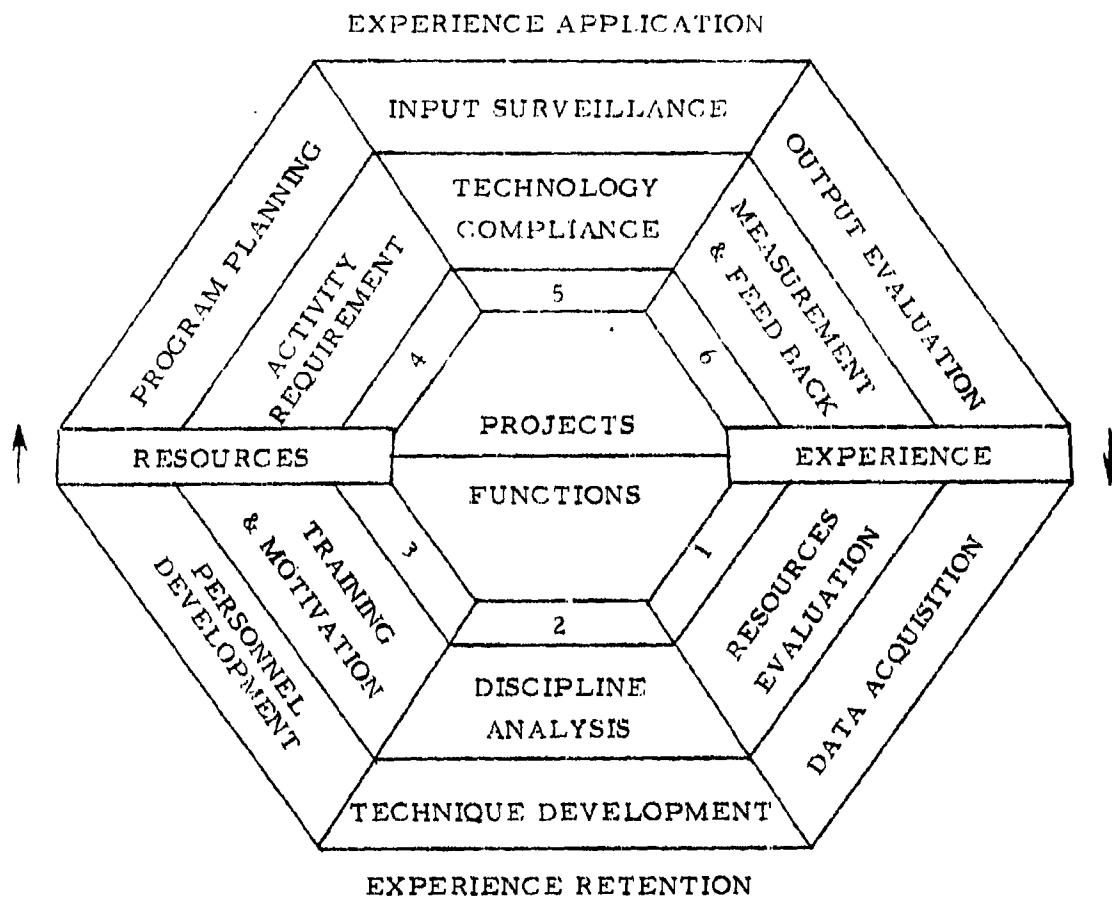


FIGURE 6  
CLOSED-LOOP HEXAGON -  
EFFECTIVENESS MANAGEMENT

#### D. CRITICAL ACTIVITIES

While it may be said that nearly all aspects of a program are critical to system effectiveness in the broad sense, the WSEIAC has identified a technical framework for relating the many system characteristics through the terms availability, dependability, and capability.

Each of these major system attributes and their principal factors must be identified, measured and controlled to acceptable limits during the program development cycle. Some examples of critical activities associated with system effectiveness characteristics are:

- Functional Flow Analysis
- Failure Mode Determination
- System Safety Analysis
- Quality Assurance
- Reliability Prediction
- Maintainability Analysis.

The WSEIAC has not emphasized the many detailed considerations within the above activities. Rather, the attempt has been to pull them together as a cohesive whole.

The fifteen-step procedure described in Section III is an attempt to relate all of these critical activities in a logical way to permit an evaluation of the composite figure of merit during successive stages of a program life-cycle.

#### E. CONCLUSION

It is a predominant conclusion of the WSEIAC that the major segments of effectiveness management described above, and the specific critical activities implied, exist today in a piecemeal fashion only, or are not present at all. The policy issues identified by Task Group V and the recommendations in this integrated report are directed toward major improvement of this situation.

In summary, the WSEIAC recommends the introduction of a degree of formalization into the management process. This can be done by integration

of the WSEIAC procedures into the AF 375 series documents so that evaluation and prediction of effectiveness/cost-effectiveness is in proper relation to the various assurance activity networks of the series.

## SECTION VI

### GENERAL CONCLUSIONS AND RECOMMENDATIONS

We have briefly discussed the basic problems which led to the formation of the WSEIAC and the approach to their solution. These problems were broadly categorized as "system effectiveness" problems. Their solution calls for a knitting together of a wide spectrum of existing management disciplines and a variety of technical specialties.

Problems have been identified and recommendations for their solution have been given. The proposed solution is a system effectiveness assurance management program. The fundamental requirement of this program is that program management utilize a formalized structure of trade-off analyses based upon the principles of cost-effectiveness optimization. The principal steps of that structure were shown in Figure 1. A large fraction of the output of the task groups was devoted to spelling out the tasks in this formalized structure and are discussed in detail in Appendix I. Significant findings of the five task groups are given in the following paragraphs.

#### A. DATA ACQUISITION

The requirement for data is so generally acknowledged as fundamental to any decision process that almost any remark concerning data has a tendency to sound trite. In spite of this, the WSEIAC survey of current data collection systems failed to discover a single one that was, of itself, capable of providing satisfactory system effectiveness data.

There are a variety of reasons for this unhappy situation:

- Data for effectiveness prediction/evaluation must be acquired by scientific planning. A proper, definitive list of the minimum data elements required to evaluate a system must be based on the needs of a system model, not generated haphazardly to satisfy specialized needs, as is the current practice.
- Current Air Force data collection systems are inflexible. They are not responsive to changing requirements.

- Current Air Force data reporting systems are subject to a variety of correctable, but currently uncorrected error sources.
- Current Air Force reporting practice is to report-by-exception. Successful event information is largely missing.
- Data on a given system is not centralized. It may never leave a contractor's plant or the base at which it is generated. On the other hand, that data which is disseminated is sent piecemeal to a variety of locations. No one agency receives a complete data package.
- Historical data does not exist in general. Current security practices and the cost of storage encourage the destruction of data after short periods of retention. For example, a survey was conducted on the availability of Atlas D ICBM development data. Virtually none was discovered although this weapon system has been obsolete for about only one year.

The recommended solution to these problems is the establishment of a centralized System Information Bank (SIB) for each system. The SIB would be maintained throughout the life of the system. During the Definition Phase and Acquisition Phase, the SIB would be established and maintained by the AFSC/SPO. During the Operational Phase, the SIB would be maintained by the Logistics Command and be supported by the using command. A summarized version of system data would be forwarded, on demand, to a System Effectiveness Information Central (SEIC), where it would be available to all on a need-to-know basis. It is recommended that the initial implementation of SEIC be under AFSC sponsorship.

A proposed charter and organization of SEIC is given in the final report of Task Group V.<sup>(10)</sup> Proposed methods of operation of SEIC are described in the final report of Task Group III.<sup>(5)</sup>

## B. TECHNIQUE DEVELOPMENT

A large portion of the WSEIAC report is devoted to illustrating the applicability of current techniques in predicting/evaluating system effectiveness/cost-effectiveness. However, these reports are not a complete set of "how-to" manuals.

Several problem areas requiring further definitive treatment are cited:

- There are no standardized techniques for the establishment of minimum acceptable quantitative system requirements, particularly when those requirements are stated as probabilities.
- There is no definitive list of basic raw data elements for any extant system, simply because an effectiveness/cost-effectiveness assurance program of the scope envisioned by the WSEIAC is unprecedented.
- Because both system effectiveness and cost-effectiveness calculations are in their infancy, there are no standardized techniques for effectiveness prediction/evaluation/demonstration.
- The use of models in management decision processes needs considerable clarification. There is a suspicious amount of evidence that current use of models falls into either of two categories:
  - If the model output agrees with a preconceived position --- use it as a vindication of judgment.
  - If the model output disagrees with a preconceived position or an accomplished fact --- suppress it.

The underlying reasons for this deplorable situation are two fold:

- untimeliness of model output, and
- lack of confidence in model output.

Complex systems tend to lead to complex models. Complex models end up as large scale computer simulations which take time to construct and

"debug," and which take additional time to reconstruct as the system changes. Thus a timely output in response to a management query becomes difficult.

Confidence in the model output is closely related to the validity, accuracy and quantity of the input data. The inadequacy of current planning for acquiring data tends to reduce confidence in model outputs.

- The methods of estimation of effectiveness parameters needs development. The one-shot nature of many current systems, combined with high unit costs, lead to small test sample sizes. The need for methods of nondestructive testing and statistical inference techniques is clearly indicated.
- Methods of system cost-effectiveness optimization need further development. Current optimization techniques are not wholly adequate to the task of manipulating a large number of variables which may be non-analytical and frequently discontinuous except for short intervals.
- Methods of incorporating risk and uncertainty into models need development. Placing confidence levels (risk) on the output of models is an unsolved problem.

The WSEIAC recommendations here are several fold:

- The problem of establishing meaningful requirements should be submitted to further study by one or more competent agencies.
- A task group should be formed for the specific purpose of defining a minimum list of basic effectiveness/cost-effectiveness raw data elements on each of the several larger AF systems. This list should be directly reflected in changes in current data collection forms and practices.
- The techniques for effectiveness/cost-effectiveness prediction provided by the WSEIAC should be regarded only as a point of departure. It is recommended that these techniques

be expanded and published in manual form.

- The entire question of the use of mathematical models in the management decision process should be subjected to a careful, definitive study with particular emphasis on (1) methods of providing timely outputs from complex models, (2) problems associated with the use of small data sample size, (3) the refinement of optimization techniques, and (4) the boundaries within which intelligent decisions may be made.

### C. PERSONNEL DEVELOPMENT

Application of the techniques recommended by the WSEIAC calls for a continuing personnel development program in the Air Force and in industry. Several Air Force problem areas have come to light here:

- SPO manning in the past has lagged contracts so that adequate program control has not always been available when required.
- The personnel system of the Air Force does not adequately recognize the experience retention aspects of personnel development.
- The personnel system of the Air Force does not adequately reflect the functional aspects of Air Force requirements.
- Experience gained on any given system is inadequately reflected, or is not reflected at all, in new system development.

Most of the difficulties cited above can be mitigated by greater utilization of existing technical staffs for development and review of technical requirements, work statements, RFQ's, etc. during the Conceptual and Definition Phases when the need is most critical.

In addition, however, existing Air Force programs for the acquisition, training, and motivation of its management and technical staffs require continued firm support. A positive program is needed to identify personnel skills and experience, and then to match these with open requirements. The

development of a system for retention of experienced personnel through sound personnel policies and good communication within management structures appears to need increased effort. (9, 10)

#### D. PROGRAM SURVEILLANCE

Admittedly, it would be desirable for a user or customer to specify exactly what he wants in terms of end performance objectives and to call for such demonstration prior to accepting delivery and issuing payment. There are many instances within the government/industry procurement program where this is indeed possible. However, for many of our complex systems which extend the state-of-the-art across a broad spectrum of technology, this simplified approach is just not feasible.

Development time scales, fiscal limitations, technical unknowns, and other constraints force the procurement into a sequential process where detailed milestones, interim objectives, and even methods to be used in arriving at the distant end objectives, are specified and controlled. Program surveillance by the customer has become a way of life; and the seller is committed to a continuous demonstration that his process for attaining the end objectives is in control.

There is no sure cure for these problems. However, surveillance by staff officers during the preparation of work statements and requirements during the Conceptual and Definition Phases, assignment of engineering development officers as Air Force Plant Representatives, holding technical direction meetings among associate contractors, and incorporation of system effectiveness/cost-effectiveness principles in the AFSC 357 series of manuals -- all will tend to improve surveillance.

#### E. GENERAL RECOMMENDATIONS

It is not the intent of this summary to present detailed recommendations

since they are covered in each task group's report, but rather to indicate briefly those principal steps which can and should be taken toward implementing the WSEIAC results as early as possible. These steps are:

- Establish a responsible office (headed by a general officer) at Air Staff level and supporting offices at all appropriate subordinate levels for the purpose of initiating, coordinating, monitoring, and implementing a system effectiveness program within the Air Force and for coordinating this program with industry.
- Reorganize current staff functions for greater use of experienced personnel in reviewing and monitoring the preparation of requirements, work statements, program plans, and requests for proposals during the Conceptual and Definition Phases.
- Adopt the proposed Air Force regulation of Task Group I<sup>(1)</sup> establishing an Air Force-wide System Effectiveness Program and applying the implementation steps suggested by Task Group V.<sup>(9)</sup>
- Initiate an in-house study to produce a "how-to" manual for developing quantitative system requirements.
- Initiate an in-house study to incorporate the content of the various WSEIAC Task Group reports into a series of "how-to" manuals.
- Adopt the mathematical framework of WSEIAC (Task Groups II and IV) and the activity networks of this report and incorporate them into the AFSC 375 series System Management Manuals and into techniques manuals which relate to system effectiveness.
- Develop and standardize definitions for system effectiveness and related terms such as those contained in the Glossary of Effectiveness/Cost-Effectiveness Terms, Appendix III of this report.

- Adopt the charter and suggested organization proposed by Task Groups III and V initiating the establishment of a System Effectiveness Information Central (SEIC) and System Information Banks (SIB's) for Air Force systems.
- Define methods of establishing meaningful, minimum acceptable requirements when they must be stated as probabilities.
- Define a minimum list of system effectiveness/cost-effectiveness data elements for each Air Force system and take steps to incorporate these elements in current data collection systems.
- Refine the use of system models in the management decision process with particular attention to the establishment of management guides to model output interpretation (decision algorithms).
- Initiate action to service test the system effectiveness/cost-effectiveness prediction techniques proposed by the WSEIAC on one or more current and proposed Air Force systems.

Finally, Headquarters AFSC should form a committee to review each of the WSEIAC task group reports in detail and to formulate long range plans for implementation.

## SECTION VII

### IMPACT ON EXISTING DISCIPLINES

#### A. A NOTE OF CAUTION

A real concern of many people is the relationship of System/Cost-Effectiveness to the other disciplines and further, its relationship to the AFSC 375 series Systems Management Manuals. If System/Cost-Effectiveness analysis is an all-encompassing discipline, then where do the other specialties such as reliability and maintainability engineering fit in? Are these disciplines eliminated? Definitely not! Consider an analogous situation. We intend to build an airplane; then we need aeronautical engineers. Do we not also need structural specialists, and the like? Clearly, these specialists play a role in creating the airplane-as-a-system. When individual system effectiveness disciplines such as reliability, human engineering, safety engineering, value, etc., must still be amplified by unique specifications, the functional flow system of the AFSC 375 series provides a framework for relating these individual elements to each other and to the mainstream of merged technological and management effort that flows from the beginning to the end of each program.

The next question that logically arises is, "Will we, by integrating these disciplines and specializations, be adding some all-powerful super-structure? Will we have to cope once more with all the funding, manning, communications and other problems associated with the addition of a new fragment to an established organization?" The answer is neither a clear yes nor a definite no. In some instances, the function already exists -- not as System/Cost-Effectiveness per se, but as some combination of loosely related elements of the management structure. These may include product assurance, reliability, systems analysis, etc., each placing some emphasis on cost-effectiveness. If the function is there in one of these impalpable forms, or if the function is missing entirely, system effectiveness problems which arise are not being cured except in an irrational, unscientific, ineffective manner which costs too much in time, performance and money. Thus, organization for system effectiveness is necessary. Funding,

manning and training for a "new" function called system/cost-effectiveness will, probably, mean change and reorientation. But if this means increased performance, reduced costs, reduced development time and more orderliness to a program, then such a change should be welcomed.

## B. LIMITATIONS

Cost-effectiveness analysis must be applied carefully. It is not a panacea nor is it a new technique. It has been a part of military planning for years. But the complexity of military tasks now requires a multidisciplinary and more systematic approach. The major utility of cost-effectiveness analysis is that it uses all the available knowledge and data in as efficient and complete a manner as is possible to give management information needed for decision making.

If they are to be of value, the results of cost-effectiveness studies must be given in terms meaningful to those who make decisions and understand the implications and results of these analyses. Thus, the analyst should appreciate the problems of communication with a broad spectrum of people including design engineers, company managers, military managers, military planners and, sometimes, congressmen and the general public.

In interpreting the results of the studies, it must be remembered that the state-of-the-art, resource constraints, political and military thinking and philosophy, enemy posture, etc., are in a constant state of flux. Thus, these results should not become associated with hard, fast, unchanging rules. A current finding that a reliability of 0.9 is best for a particular component should not become permanent dogma. The results should never be the basis for hindering research. Rather, they should provide guidelines for further exploration or tests designed to yield more fruitful information on which to base decisions.

The limitations of cost-effectiveness studies have already been suggested in the foregoing paragraphs. The reader should bear in mind that, whatever shortcomings or dangers may be associated with analytical studies such as those proposed by the WSEIAC, decisions based on intuition, experience which has not been thoroughly analyzed, or a sample of personal opinion (deep-seated feeling) are certainly less defensible and more subject to

omissions of important factors. One would not build a bridge by intuitive design, overlooking sound structural engineering practice; yet, many unknowns exist in regard to material mechanics and random loading behavior of structures.

Although, in a sense, statements on limitations of cost-effectiveness analyses may be regarded as platitudes, we present some of them here as reminders.

- Cost-effectiveness indices cannot be meaningful unless derived from a model which represents the "real world" fairly closely. Reality should not be buried under mountains of detail nor does great detail, by itself, create reality in a model.

- It must be remembered that cost-effectiveness analysis is an iterative process. Early results should not be permitted to create such a lasting impression (favorable or unfavorable) as to lead one to ignore the results of later refinements. This could lead to disillusionment on the part of all concerned and eventually to abandonment of a valuable tool.

- Cost-effectiveness analysis can never replace good engineering and management practices. It should be regarded as a supplementary tool to provide meaningful information. Final decisions must still be based upon sound judgment. This must be particularly emphasized since too many political, psychological (e.g., an individual's drive to solve a particular problem), prestige value, and other factors cannot be considered in a satisfactory manner at this time in such analyses.

- When results are sensitive to factors associated with high degrees of risk or uncertainty, "warning signs" must be posted. The results must then be used judiciously in making decisions.

In much of what has been said earlier, there is an obvious attempt to build up the importance of cost-effectiveness consciousness. Considerable emphasis has been placed on developing models for obtaining cost-effectiveness indices and optimization thereof. However, it must be remembered that these do not provide a final answer. They do provide guidelines, but judgment must still play a large part.

Perhaps this is best expressed by Dr. Alain Enthoven's statement:<sup>1/</sup>  
"Do judgment and experience have no place in this approach to choice of weapon systems and strategy and design of the defense programs? Quite the contrary. The statement that the issue is judgment versus computers is a red herring. Ultimately all policies are made and all weapon systems are chosen on the basis of judgments. There is no other way and there never will be. The question is whether those judgments have to be made in the fog of inadequate and inaccurate data, unclear and indefinite issues, and a welter of conflicting personal opinions, or whether they can be made on the basis of adequate, reliable information, relevant experience, and clearly drawn issues. The point is to render unto computers the things that are computers' and to judgment the things that are judgment's. In the end, there is no question that analysis is but an aid to judgment and that, as in the case of God and Caesar, judgment is supreme."

Thus, although there are limitations in this modeling process to obtain cost-effectiveness indices, it must be remembered that this approach allows us to:

- organize and set into proper perspective the many alternatives of the problem;
- establish many "if-then" statements, pertaining to the alternatives of the problem;
- evaluate properly data uncertainties;
- examine many cases quickly which would require years of simulated combat to test; and
- explore systematically those cases which cannot be tested (you cannot go to war to test system effectiveness).

And another caution. There are still many unsolved problems. The task group reports are not "how-to" manuals. However, WSEIAC has

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<sup>1/</sup> From a lecture, "Decision Theory and Systems Analysis," delivered during the Distinguished Lecture Series, sponsored by the Board of Trade Science Bureau, Washington, D. C., December 5, 1963.

provided more than the nucleus of a solution.

Many positive recommendations have been presented. These include a summarization of current cost-effectiveness techniques and a task analysis that identifies critical activities to be meshed with the current Air Force management series of manuals as an activity network governing system effectiveness assurance.

APPENDIX I

TASK ANALYSIS OF A  
SYSTEM EFFECTIVENESS/COST-EFFECTIVENESS  
PREDICTION/EVALUATION/AUGMENTATION CYCLE

## APPENDIX I

### TASK ANALYSIS OF A SYSTEM EFFECTIVENESS/COST-EFFECTIVENESS PREDICTION/EVALUATION/AUGMENTATION CYCLE

#### A. INTRODUCTION

It is the purpose of this appendix to amplify the earlier discussion of the fifteen steps for conducting a System Effectiveness/Cost-Effectiveness Prediction, Evaluation and Augmentation Cycle. Each step corresponds to a block in Figure 1. Since there is a considerable amount of detail, a more detailed foldout of Figure 1 has been inserted (Figure 14) to give the total task sequence on one chart. It will be helpful to fold out Figure 14, page 125, at this time.

Each step is discussed in detail and in numerical succession, indicating the general content of each block, problem areas which exist, and, whenever possible, recommended solutions. Pertinent considerations appropriate to the various phases of system life-cycle are also included. Following this exposition, an example analysis applicable to Conceptual Phase studies is given in Appendix II to illustrate the task analysis.

## B. BLOCK 1.0 MISSION DEFINITION

The output of the mission selection analyses conducted in the Conceptual Phase and pre-Conceptual Phase is a statement of what the system is to accomplish. Historically, this output covers the end-item functions which are to be accomplished (target destruction, reconnaissance, space exploration, etc.) and the conditions and geographic locations within which these functions are to take place. The optimization processes that take place in the succeeding Definition and Acquisition Phases consist mainly of synthesizing alternate means of meeting stated objectives, evaluating them, and selecting the combination of such alternatives which secures the most favorable cost-effectiveness relationship.

Accordingly, it follows that if the statement of program objectives severely limits the alternatives which can be considered, the ability to achieve optimum cost-effectiveness during later phases is correspondingly reduced. Thus, the statement of program objectives and mission derived from studies during the Conceptual Phase analyses should tend to define what is to be done rather than specifically direct how the task is to be accomplished. It should be noted, however, that additional constraint and relationship data must be provided in order that systems and resource use selection correspond to the basis on which the mission was initially justified.

It is a fundamental requirement of the methods recommended by the WSEIAC that a clear and unambiguous statement of the mission of a system be obtained. This definition should contain:

- 1.1 functional description (purpose) of system, and
- 1.2 system quantitative requirements.

A functional description of the system should be directly derivable from an ROC or QOR. Although this description may be somewhat modified at the end of the Acquisition Phase, the ROC and QOR should remain the fundamental reference.

The WSEIAC has identified a problem area with respect to the establishment of quantitative requirements. Some system requirements (e.g.,

range) will be immediately evident from the ROC or QOR. For these, the statement of minimum acceptable performance levels will be straightforward. For others, especially those for composite system attributes such as reliability and availability, minimum acceptable values will not be evident from the ROC or QOR. In these latter cases the WSEIAC recommends that comparative analysis be employed during the Conceptual Phase to establish tentative requirements. Such requirements, documented in a TSOR become the guiding input to the Definition Phase where they can be further refined to become a firm set of requirements in the SOR.

The problem area that the WSEIAC has identified in this process is:

- There is no generally accepted set of techniques for determining minimum acceptable requirements that holds for all the factors of effectiveness, particularly for those factors which are stated as probabilities. This problem may be paraphrased as: "How much is enough? "

## C. BLOCK 2.0 RESOURCES

Resources usually evidence themselves as a practical constraint on the development and procurement of a system. There are four principal areas of consideration here:

- 2.1 budget
- 2.2 SPO manning
- 2.3 industry capacity
- 2.4 technology.

Current budgetary practices constitute a limitation on the full exploitation of the System Effectiveness/Cost-Effectiveness prediction techniques currently available. Specifically:

- A trade-off based on System Effectiveness/Cost-Effectiveness prediction techniques in the Conceptual Phase calls for a balance between investment costs (AFSC) and support costs (AFLC and using command) for the life of the system. This is contrary to current budgetary practices which allocate funds by command and by program element.
- Trade-off studies based on System Effectiveness/Cost-Effectiveness prediction techniques in the Definition and Acquisition Phases require recognition that greater expenditures from the AFSC pocket can result in less expenditures for the using and support commands. Past budgetary practices did not encourage consideration of this attitude.

#### D. BLOCK 3.0 SYSTEM DESCRIPTION

The depth of system description (and, consequently, the detail in System Effectiveness/Cost-Effectiveness prediction) depends upon the phase of the system life cycle. System description consists of either:

- 3.1 identification of alternative system configurations, or
- 3.2 configuration documentation, followed by
- 3.3 system summary description.

The ability to optimize a system depends on the availability of alternate means of meeting the requirements. Alternatives include the means, approaches, or techniques which can be employed to meet the stated requirements within the constraints of the resources. Obviously, if no alternatives present themselves, or if they are ruled out by the statement of requirements and resources, there is no problem in selection. It also follows that when alternatives do present themselves, decision between them is required. If the system is to be optimized with respect to cost-effectiveness, then the optimization process must extend to each decision made on the alternatives presented.

Table I shows an example of some of the types of alternatives considered in optimization studies.

It is possible to arrive at the optimum system of a given type by designing a great number of alternative systems, estimating cost and effectiveness for each, and simply selecting the best one. However, the large number of man-hours required to do this renders such an approach impractical. A more practical approach is to consider only a very few basic configurations or candidate systems within a given system type. A completely adequate cost-effectiveness optimization of the system can often be accomplished with as little as one basic configuration. However, due to the small number of basic configurations thus explored, it is necessary that each basic configuration be optimized within itself. This is accomplished by synthesizing and evaluating variations or alternatives at several levels within the basic configuration. These alternatives may take the form of either physical or performance characteristics.

**TABLE I**  
**TYPICAL ALTERNATIVES**  
**POSSIBLE IN COST-EFFECTIVENESS**  
**OPTIMIZATION**

**Basic Concept**

**Manned Versus Unmanned**

**Liquid Versus Solid Rockets**

**System and Subsystem Type**

**Battery power versus generation**

**Materials Choice**

**System and Subsystem Configuration**

**Redundancy**

**Maintenance**

**Hi-Reliability versus MIL Std Parts**

**Operational modes**

Each military system has a number of physical characteristics that affect cost, performance and effectiveness. A list of physical characteristics to cover all systems will not be attempted here. A few of those common to most systems include weight, volume, shape, energy levels, mechanical and electrical packaging, and environmental capabilities. The physical characteristics of a system affect the cost elements incurred in development, procurement and support. There is obviously a broad range of cost sensitivity as cost elements are compared for different design alternatives of a given system requirement as well as for different technology alternatives within a given design alternative.

When one considers the area of performance characteristics of military systems, it is difficult to prepare a comprehensive listing, and few performance characteristics are common. Typical performance characteristics for a few military systems include: accuracy, speed, thrust, memory capacity, computational capability, signal to noise ratio, range, power output, discrimination, etc. Relationships between cost elements and performance characteristics are fertile areas for optimization. A particular cost element will vary as the performance characteristic varies over the range of values possible for the design alternative. For a given requirement level of a performance characteristic, cost variation as a function of the different design and technology alternatives within a design alternative, are of prime importance. The constraints on performance characteristics are generally set by scientific, engineering, and manufacturing knowledge and capabilities.

In listing the alternatives, primary importance should be given to those which have a significant impact on cost or the resources established in the statement of requirements. A preliminary analysis of an initial system design can ordinarily indicate the major impact areas.

The number of alternatives to be considered in the optimization process can, in many cases, be reduced by screening these alternatives against the

available resources established in the statement of requirements. In the area of cost, physical characteristic constraint relations established outside the cost area will often bound and limit the feasibility or scope of alternatives.

As an example of such screening, let us look at a case wherein an isotope power source is being considered as an alternative to a power system design more compatible with current state-of-the-art. If the required date for system operational capability is relatively early in time, the isotope power source may be automatically ruled out by lack of availability by the required date.

An example of an alternate type of screening problem could occur when comparing the same isotope energy source against an operational date stated as a variable. Assuming that system effectiveness or value decreases as the operational date is delayed, it may be possible to eliminate the isotope energy source from further detailed consideration on the basis that the cost or effectiveness gains associated therewith do not compare favorably with the value or effectiveness lost due to the corresponding slide in operational date.

In preparing a list of alternatives, one should associate them with the level at which decisions upon the alternatives are to be made. At system level, decisions should be made on alternatives which impact on the basic system configuration or operational mode. Decisions which do not directly or substantially affect basic configuration and operational mode should be made at lower levels using trade-off factors developed for the entire system. If such lower level decisions are attempted as a part of the over-all system optimization process, the scope of the system level problem may become unmanageable. It is recognized, however, that the basic system may change significantly as a result of optimizations at subsystem level. Further, the trade-offs and optimizations made at subcontractors level with a single sub-assembly or black box may have far-reaching effect on system effectiveness. Thus, any system for handling cost-effectiveness must permit optimization to feed both up and down through the various system levels and/or tiers of customer/contractor/subcontractor. The process of feeding up and down

through the system must be recognized as an iterative one, wherein it may be necessary to reiterate some of the lower level suboptimizations to insure that the basic system changes have not altered previously established conclusions.

During the Conceptual Phase, steps 3.1 (identify alternative system configurations) and 3.3 (system summary description) form a logical sequence for system description. In the late Definition Phase and Acquisition Phase, the emphasis increasingly shifts to 3.2 (configuration documentation) followed by 3.3. The latter activity, common to both sequences, contains as a minimum:

- 3.3.1 specification of levels of system organization;
- 3.3.2 specification of STOC<sup>2/</sup> and their time lines by equipment/function;
- 3.3.3 specification of physical factors;
- 3.3.4 specification of support policy by type and time line; and
- 3.3.5 specification of use plan.

This summary description must reflect all those features of system structure which can affect either:

- the estimation of effectiveness, or
- a system effectiveness/cost-effectiveness trade-off analysis.

The distinction here between effectiveness and cost-effectiveness is important. A particular system feature may be uncontrollable, and hence not capable of manipulation for cost-effectiveness trade-off analysis, but it must be included in an effectiveness calculation in order to estimate current or predicted status.

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<sup>2/</sup> Standard Tactical Operating Conditions

During the Definition and Acquisition Phases the system is increasingly defined on paper. On an iterative basis, the following activities of configuration documentation (3.2) occur:

- 3.2.1 perform/review function analysis;
- 3.2.2 make/review engineering drawings;
- 3.2.3 assemble/review physical factors summary document; they are conducted on an "as pertinent" basis.

These activities, taken jointly, lead to further detailed documentation activities:

- 3.2.4 perform/review equipment operating time line analysis;
- 3.2.5 assemble/review integrated task index;
- 3.2.6 assemble/review unit manning document;
- 3.2.7 assemble/review reliability indices report;
- 3.2.8 assemble/review data handbook;
- 3.2.9 assemble/review provisioning requirements document;
- 3.2.10 assemble/review cost indices document;
- 3.2.11 assemble/review planning factors document;

The content of these activities must be reflected in (3.3) system summary description.

The WSEIAC has emphasized by illustrative example that each of the above activities is essential to an adequate system description. A problem area has been identified in the area of cost indices documentation. Currently, cost data is not summarized in a form suitable for use in System Effectiveness/Cost-Effectiveness calculations.<sup>(7)</sup>

#### E. BLOCK 4.0 FIGURES OF MERIT

A figure of merit is a statement which relates mission objectives (ROC or QOR) to quantitative system requirements (SOR). It is a statement of the ability of a system to meet an operational need, including the recognition of the risk and uncertainty that are fundamental characteristics of the military mission.

Risk is synonymous with odds. Recognition of risk leads to the statement of a figure of merit in probabilistic terms.

Uncertainty is associated with lack of knowledge or empirical data necessary to establish value or range. Recognition of uncertainty leads to the consideration of the possible (unpleasant) surprises of the future. Such considerations reflect themselves in alternative (potential) mission objectives and alternative figures of merit.

##### 1. Principal Measure

The most comprehensive figures of merit are system effectiveness and cost-effectiveness. It is the purpose of this section to describe the WSEIAC concepts of effectiveness and cost-effectiveness in some detail.

System effectiveness is a quantitative measure of the extent to which a system may be expected to achieve a set of specific mission requirements.

System effectiveness prediction/evaluation is based upon probabilistic concepts. A suitable format for expressing system effectiveness is "the probability (x) that a system can successfully accomplish a specific mission directive at a random point in time, following the establishment of an alarm condition, shall be greater than (y) with probability (z)." This statement is meaningful only in relation to a test program and hence implies that the SOR requires a minimum acceptable demonstration test program.

System effectiveness may be regarded to be a function of three major system attributes: availability (A), dependability (D) and capability (C).

Availability (A) is a measure of the system condition at the start of the mission, when the mission is called for at an unknown (random) point in time.

This factor of effectiveness has also been referred to in the past (not always accurately) as Operational Availability, Operational Readiness, Alert Readiness, Ready Rate, and Real In-Commission Rate. It is usually expressed as: (See Glossary)

$$A = \frac{\bar{t}_i}{\bar{t}_a + \bar{t}_d}$$

where

$\bar{t}_i$  = mean time between system interruptions

$\bar{t}_a$  = mean time assigned to the up condition

$\bar{t}_d$  = mean time assigned to the down condition.

A system interruption is defined to be any event which removes the system from its alert status. Thus, failures (known or unknown), planned or unplanned maintenance, and administrative actions (such as crew training exercises) are all potential causes of system interruption.

An estimate ( $\hat{A}$ ) of steady state availability can be obtained by calculating:

$$\hat{A} = \frac{\text{total time system is in true up condition}}{\text{total calendar time of observation of system}}$$

The denominator of this expression is directly observable. The numerator however, is directly observable only when all failures are observable at (or near) the instant of occurrence. In general, this will not be the situation, and in some cases, fairly complicated methods of statistical inference may have to be employed to estimate the true status of the system.<sup>(4)</sup>

Availability is calculated as the expected fraction of time that a system is in an operable condition in a specified time interval.

Availability means the probability that a system will be operable and ready to initiate a mission at a random point in time.

Availability encompasses:

- system failure rates,
- system repair rates,
- system maintenance policy/procedures,
- personnel factors,
- system support policy.

Proper expressions for availability always reflect explicit measures of:

- personnel,
- procedures,
- hardware.

Dependability is a measure of the system condition(s) at one or more points during the mission; given the system condition(s) at the start of the mission. It will usually be stated as the probability (or probabilities or other suitable mission oriented measure) that the system will enter and/or occupy any one of its significant states during a specified mission. It specifically includes, but is not limited to, equipment reliability during the mission. For example, if repair is possible during a mission, dependability will include the effects of the repair capability on mission success. On the other hand, if no repair potentiality exists, but there are backup modes of performance, proper expressions for dependability must specifically account for the probabilities of requiring the use of the alternative (and possibly degraded) modes of performance.<sup>(3, 7)</sup>

The formulation of dependability expressions is strongly influenced by the type of system and system utilization; thus, no single generalized expression can be written for dependability.

Dependability accounts for a variety of system aspects, for example:

- reliability,
- ground vulnerability
- flight vulnerability } (survivability),
- penetrability,
- repairability.

The meaning of dependability will vary depending upon the significance attached to the various system conditions which can occur during the mission. For example, the dependability expressions for an ICBM are simply the probabilities of successful survival, launch, flight, and penetration under tactical conditions. For a manned aircraft with multimode delivery capability, the dependability expressions will usually be the probabilities of being required to use each of the various possible modes of weapon delivery. On the other hand, the time spent in each possible system state during the mission may be the crucial factor in dependability. In this case, the dependability expressions may be chosen to be either the probability of spending a time " $\tau$ " in any given state, or the expected fraction of time spent in any given state during the mission.

Survivability is the probability that a system will either (1) be removed from the threatened environment before it can be attacked (as with warning), or (2) "ride out" some anticipated attack. In the first instance, the basic parameters are the amount of reliable warning time and the reaction time from "alerted" through reaching a "safe" environment. In the latter case, which is commonly assumed for hard-site ballistic missiles, many things can become important: blast hardness (i. e., resistance to overpressure); electronic hardness; dispersal mobility; deception; active defense; and above all, the weight or severity of the expected attack. If a weapon system is intended to provide a credible deterrent threat for a substantial time (say days or even weeks) after initiation of hostilities, it must not only survive possible missile attacks, but perhaps also manned-bomber attacks. In addition, such extensive periods of operation must be supported in the likely absence of "normal" (i. e., peacetime) services like commercial power, telephones, and even highway travel.

Reliability is the probability that an "available" system (i. e., in-commission and having no hidden defects detectable by monitoring or periodic checkout) will operate without failure during the mission. In the case of an ICBM, the reliability aspect of dependability is usually considered to be the product of launch reliability and flight reliability. Launch reliability

can be thought of as being made up of Command Reliability (accomplish the specified pre-launch procedures within the allotted time), and Initiation Reliability (perform the irreversible or "one-shot" sequence of launch events such as firing squibs, door ordnance, igniters, etc.). All three of these sub-elements depend also in some fashion on the quality of maintenance activities accomplished during the period of strategic alert. In other words, they are affected by the same things as the availability expression though not necessarily in the identical manner. For example, the pre-launch procedures are often similar and sometimes identical to periodic exercises performed for verification of alert status.

For ballistic missiles, flight reliability ordinarily includes, in addition to propulsion and control and other factors, proper engine cut-off, staging, and guidance. For manned aircraft, both hardware performance and human performance (correct navigation to target, aiming, and weapon delivery) are involved. For a Jammer System, it would include detection of enemy radiation, selection of response mode, and subsequent radiation of the proper jamming signals. Once again, the hardware reliability is related to the quality of maintenance in the ground environment.

Penetrability is the probability that a weapon system will survive a defense environment and arrive at the target intact. For manned aircraft, this probability is a function of such things as the penetration mode (for example, low level flight to avoid detection), speed, maneuvers, electronic countermeasures, decoys, etc. For ballistic missiles, for example, penetrability may be expected to be 100 per cent against a no-defense environment, while anti-ICBM environments make penetration aids and terminal maneuvers important. This is an area where time is also certain to be a factor; chronological improvements can be expected in the quality of both offensive and defensive tactics, so particular levels of either must be associated with a particular point in time.

Capability is a measure of the ability of a system to achieve the mission objectives; given the system condition(s) during the mission. It specifically accounts for the performance spectrum of a system. For example, such familiar things as accuracy, range, payload, lethality<sup>3/</sup> and information retrieval rate determine the capability of a system.<sup>(3)</sup>

Like dependability, capability is clearly peculiar to each system (and proposed mission), so that no unique set of expressions applies generally to all systems.

In general, capability expressions are a measure of the "worth" or "value" of any system state. The measure of worth can be stated variously as the probability of accomplishing the mission objectives while in some given state; as the expected number of targets destroyed per sortie; as the probability of track, given detection; and so forth.

Of the three factors -- availability, dependability, and capability -- the last is usually regarded to be the most direct expression of the intent of an SOR. If availability and dependability express the chances of getting on the ballot -- capability is an expression of the ballot count.

## 2. Additional Considerations

In addition to the basic factors, availability, dependability, and capability, there are certain other qualities of a weapon system which have an impact on total effectiveness, though they are less susceptible to direct quantification. For example, the ability to retarget a ballistic missile

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<sup>3/</sup> Lethality is defined here as the probability that weapon effects will destroy the target. For a point target, this is a function of the accuracy of delivery, usually expressed as a Circular Error Probability (CEP), and the lethal radius (LR), which is in turn a function of warhead yield, burst altitude, and target hardness. For area targets, lethality can be related to these same parameters through simple nomograms, which can give (in addition to simple probability estimates) the expected fraction of an area target that will be destroyed. (This type of information is also available for multiple warheads, or multiple weapon launches.) The latter quantity can be considered a figure of merit attributable to such elements as yield, aim point, CEP and height of burst.<sup>(8)</sup>

quickly and simply may allow a reduction in the extent of overlapping coverage for high-priority targets, and thus permit either an improvement in the long-term coverage of secondary targets, or alternatively, a reduction in the required size (and cost) of the total force structure. The inherent flexibilities of manned systems are likewise significant.

For many weapon systems safety is a paramount consideration. Unless safety features are carefully considered during the development process, there is a significant probability that a system may be activated by error (operator, maintenance, spurious signals, failure of a critical circuit or function, etc.). Military and strategic consequences of such errors are enormous, and their prevention is frequently an overriding factor in the choice of system design and configuration.

For some systems security is a vital factor. What is the probability that a saboteur could take over a system and render it incapable of use, or worse, use it against us? Although it may be difficult to quantify both safety and security, there can be no question that system design and operation criteria must reflect a thorough assessment of these real probabilities, and due consideration should be given to their inclusion in a total effectiveness model.

### 3. Selecting a Figure of Merit

A cost-effectiveness optimization process is essentially one of achieving a combination of resources and attained effectiveness that is best by some FOM. In defining an appropriate FOM, one is faced with a problem similar to that of stating in precise, quantifiable terms the rules or criteria for choosing the "best" painting or "best" automobile. These examples do have some quantifiable (though not necessarily pertinent) characteristics, such as the size of the painting, rating of the artist, or the dimensions (roominess) of the automobile; however, artistic judgment and user experience, respectively, are also factors in the final choice. In the same sense, the choice of the best weapon system is greatly influenced by the use of good engineering, economic, and operational judgment.

The only general rule to be followed in selecting an FOM is that it should include as many system significant factors as possible so that the optimization process will reflect a truly balanced trade-off between alternatives. But in order to keep the optimization problem within manageable proportions, the system and the boundaries must be explicitly defined. This will restrict the choice of parameters in the optimization model. The purchaser of a new automobile, for example, may or may not consider the service policies of the manufacturer and dealer. If he does, the system is both the automobile and service policies; if he does not, the system is only the automobile. In attempting to optimize a weapon system such as a bomber, it is necessary to consider whether the system is to be defined as a single bomber, a squadron of bombers, or the complete bomber fleet. It is possible that optimizing with respect to a single bomber (a sub-optimization) may not yield the optimum "squadron" system, which may not, in turn, give a force-wide optimum.

A further restriction in the size of the optimization problem may be obtained if some factors may be considered fixed by results of previous analyses (perhaps sub-optimizations). A maintenance trouble-shooting routine, for example, might normally be considered as a variable factor, but past analysis in this area might be used to select a particular routine applicable to the system under study, or perhaps to restrict the range to several alternatives.

It is impossible to establish rigid ground rules or procedures for formulating a criterion for optimizing cost-effectiveness of a system. The answers to the following two basic questions, however, will provide a great deal of insight for such formulation:

- Why is the system being developed?
- What physical and economic limitations exist?

The answer to the first question is essentially given by the mission definition for the system. Where possible, the mission definition should be translated into quantitative system requirements -- a difficult task in many

cases. A performance measure such as kill-probability for a bomber may be assignable, but the bomber may also have a mission to act as a deterrent -- a measure that is difficult (if not impossible) to quantify. It is for this type of multimission case that judgment will become especially important. Even if quantitative requirements can be placed on all mission types, weighting factors will have to be introduced to quantify the relative importance of each mission.

Factors that have relatively little impact on over-all effectiveness or cost can be considered to be fixed -- or, possibly, ignored. There is, of course, a risk involved if factors chosen to be fixed or unimportant would have had a significant effect if they had been allowed to vary. Factors that fall in this "gray area" may have constraints imposed upon them in such a manner that the more detailed analysis to be performed in the optimization process will indicate final disposition. For example, if a questionable factor might have a monotonic influence on effectiveness, consideration of only extreme values might be all that is necessary to determine the significance of this influence.

In many areas cost-effectiveness criteria or measures are commonly accepted. These are often stated in terms of dollars per unit of task performed. These measures are analogous to sales prices for units of measureable materials used in the civilian market, such as dollars per gallon, dollars per pound, etc. These measures are easily understood and lend themselves to the spirit of the drive to produce or purchase the most for the least. Table II lists some examples of cost-effectiveness criteria and the field of endeavor in which they are used.

TABLE II  
EXAMPLES OF COST-EFFECTIVENESS CRITERIA  
IN VARIOUS AREAS OF ENDEAVOR

| <u>Area of Endeavor</u> | <u>Example of a Cost-Effectiveness Criterion*</u> |
|-------------------------|---------------------------------------------------|
| <b>Non-Military:</b>    |                                                   |
| Building                | Dollars per square foot                           |
| Air passenger           | Dollars per passenger mile                        |
| Freight                 | Dollars per ton mile                              |
| Computer                | Dollars per bit                                   |
| Communications          | Dollars per message unit                          |
| Electricity             | Dollars per kilowatt hour                         |
| Gas                     | Dollars per cubic foot                            |
| Public highways         | Dollars per mile                                  |
| Farming                 | Dollars per acre                                  |
| <b>Military:</b>        |                                                   |
| Launch vehicles         | Dollars per pound payload in orbit                |
| Satellites              | Dollars per hour of successful operation in orbit |
| Missiles                | Dollars per kill                                  |
| Interceptors            | Dollars per intercept                             |

\* Cost per successful effort is different for military than for non-military products, since success is usually probabilistic in nature in the military situations.

## F. BLOCK 5.0 SPECIFICATION OF ACCOUNTABLE FACTORS

As a preliminary to model construction, and following mission definition, system description, and specification of figures of merit, it is necessary to spell out the boundary conditions of the analysis to be conducted.

First, the (5.1) Level of Accountability must be specified.

5.1.1 What are the System Interfaces? Is the system a single missile, or is it a wing? Is it to be regarded as an independent entity, or is it to be considered on a force mix basis?

5.1.2 What is the Level of Analysis? Is a missile a least unit? a subsystem? a launch site replaceable module? a piece part?

5.1.3 What are the variables of the Analysis? The variables of an analysis are of two kinds:

- controllable, or
- fixed.

Both are required to estimate effectiveness. Only the former is subject to trade-off. Expected trade-offs should be identified before model construction commences. Typical variables are:

- failure rates by mode of operation and by subsystem, module, or piece part;
- downtime distributions categorized by equipment and reason;
- test coverage by subsystem and test designation;
- distribution of task durations by test designation;
- personnel factors;
- spares provisioning;
- deployment ;
- maintenance factors.

It is also necessary to (5.2) Define Constraints particularly in the areas of

- 5.2.1 Data
- 5.2.2 Schedule
- 5.2.3 Burden
- 5.2.4 Resources
- 5.2.5 Acceptable risk and uncertainty
- 5.2.6 Physical environment

Those (5.3) Personnel factors which it is desired to see reflected in the model construction and which have an impact on effectiveness should be carefully spelled out, for example;

- 5.3.1 Manning level
- 5.3.2 Organization
- 5.3.3 Characteristics
  - 5.3.3.1 AFSC (Skill Level)
  - 5.3.3.2 Task Duration
  - 5.3.3.3 Errors of Commission and Omission

Those (5.4) Procedural factors which it is desired to see reflected in the model construction and which have impact on effectiveness should be carefully delineated, for example;

- 5.4.1 Maintenance Policy
  - 5.4.1.1 Type
  - 5.4.1.2 Time Line
- 5.4.2 Software

Those (5.5) Hardware factors which it is desired to see reflected in the model construction, and which have an impact on effectiveness, should be carefully noted, for example;

- 5.5.1 System Organization (subsystems, modules, etc.)
- 5.5.2 Equipment Operating Time Line by Mode and Equipment
- 5.5.3 Failure Distributions by Mode and Equipment

The (5.6) Logistics factors and the (5.7) Scenario of system planned use should be accounted for. Table III presents a typical checklist of accountable factors. This is, of course, only a partial checklist of accountable factors. It serves only as a point of departure.

#### G. BLOCK 6.0 IDENTIFY DATA SOURCES

The structure of a model must be tailored to fit the type of data available. This is, of course, a two way road. The type of question to be answered and the type of trade-off to be considered imply a need for certain types of data. The early identification of data sources aids in formulating a proper model structure and alerts management to include timely planning for (8.0) Data Acquisition.

**TABLE III**  
**TYPICAL CHECKLIST FOR**  
**IDENTIFICATION OF ACCOUNTABLE FACTORS**

|                                                                  |                                                  |
|------------------------------------------------------------------|--------------------------------------------------|
| <b>System Hardware Description</b>                               | <b>Spares</b>                                    |
| • Modes of operation                                             | • Provisioning                                   |
| • Hardware organization                                          | • Storage                                        |
|                                                                  | • Packaging                                      |
| <b>Compatibility</b><br>(e.g., Electromagnetic<br>Compatibility) | <b>Support Equipment</b>                         |
|                                                                  | • Test                                           |
| <b>Survivability</b>                                             | • Transport                                      |
| <b>Vulnerability</b>                                             | • Maintenance                                    |
| <b>Deployment</b>                                                | • Facilities                                     |
| <b>Geographic Factors</b>                                        | <b>Procedures/Policies</b>                       |
| • Deployment                                                     | • Operating                                      |
| • Geology                                                        | • Repair                                         |
| • Climate                                                        | • Inspection/Maintenance                         |
| • Atmospheric phenomena                                          | • Testing                                        |
| <b>Personnel</b>                                                 | <b>System Interfaces</b>                         |
| • Operating                                                      | • Support systems                                |
| • Maintenance                                                    | • Force mix                                      |
| <b>Transportation</b>                                            | • Strategic Integrated<br>Operations Plan (SIOP) |

## H. BLOCK 7.0 MODEL CONSTRUCTION

The WSEIAC views model construction as a four step process:

- 7.1 List Assumptions
- 7.2 List Variables and Define Model Parameters
- 7.3 Construct Effectiveness Model(s)
- 7.4 Construct Cost Model(s)

The (7.1) listing of assumptions is crucial. The usefulness of a model can be severely limited if the assumptions violate reality. A clear statement of assumptions is therefore a necessity in judging the validity of the results of a model exercise.

The (7.2) listing variables and defining the model parameters permits a comparison of the structure of the model with the list of accountable factors (5.)). It provides a means of judging the completeness of the model structure.

A variable is defined here as a quantity, the use of which, when varied, will result in variations in resources or the effectiveness with which the program objectives are accomplished. The step (7.2) in the task analysis consists of identifying those variables which will influence the evaluation of each alternative listed from (3.1).

Table IV shows examples of variables which can influence the choice of alternatives. In a cost-effectiveness optimization, it is evident that, although many variables exist and could influence final selection of an alternative approach, the variables which are significant can be limited to those which have an impact on cost, resources available, or the effectiveness with which the system performs its function. Model parameters which do not influence these quantities significantly should not be included in the optimization process.

Variables can be screened to a certain extent. In general, some variables can be arbitrarily treated as fixed quantities as a result of the statement of requirements, limitations on resources, or other previously

**TABLE IV**  
**TYPICAL VARIABLES INFLUENCING**  
**EFFECTIVENESS/COST-EFFECTIVENESS**  
**EVALUATION OF ALTERNATIVES**

**Cost**  
**Weight**  
**Payload Carried**  
**Mission Length**  
**State-of-the-Art**  
**Time Required**  
**Reliability**  
**Safety**  
**Maintenance**  
**Availability**  
**Vulnerability**  
**Survivability**

established decisions on the program. In other cases, a legitimate variable can be treated as a fixed quantity initially. Then, after initial optimizations have been completed, the effect of altering the variable can be expressed in terms of impact on the final answer. In many cases, judicious fixing of variables in this manner can save a large amount of manpower expenditure if the decision to fix the variable is based upon probable insensitivities of the answer to the magnitude of variation expected.

The range of each variable to be considered should, for economy of analysis effort, be limited. Constraints on physical characteristics often limit the range of performance characteristics or other variables which can be considered. Preliminary sensitivity analysis, rough-cut analysis, or an extreme (maximum and minimum) value analysis are also useful in indicating probable limits of variables. Variables thus limited should be re-examined after completion of the optimization study. If a definite optimum point is reached within the limits of each variable, it is generally safe to assume that the limits established were reasonable.

A model parameter, as used here, denotes a specific symbol (or name of a quantity) which enters into calculating system effectiveness/cost-effectiveness. Parameters may, themselves, be variables, or variables may be compounded of parameters; but parameters will always be the smallest identifiable units of a model. They define the fine structure of a model. Care must be taken to select parameters which can be estimated from available data and which at the same time permit the study of variations in independently controllable factors. For example, the mission reliability of a single unit should not be treated as a lumped value, but should rather be expressed in terms of the two independently controllable parameters, the mission duration and the unit failure rate.

The WSEIAC has outlined a specific, basic, analytical model (see BLOCK 4.0 discussion) on which to (7.3) construct effectiveness model(s). In its symbolic form, effectiveness (E) is given by,

$$E = \bar{A}' [D] \bar{C}$$

where

$E$  = System Effectiveness is a measure of the extent to which a system may be expected to achieve a set of specific mission requirements and is a function of availability, dependability and capability.

$\bar{A}$  = Availability is a measure of the system condition at the start of a mission and is a function of the relationships among hardware, personnel and procedures.

$[D]$  = Dependability is a quantitative measure of the system condition at one or more points during the mission, given the system condition(s) at the start of the mission, and may be stated as the probability (or probabilities or other suitable mission oriented measure) that the system will enter and/or occupy any one of its significant states during a specified mission.

$\bar{C}$  = Capability is a measure of the ability of a system to achieve the mission objectives, given the system condition(s) during the mission, and specifically accounts for the performance spectrum of a system.

The first step in implementing this analytical definition is to describe the significantly different system "states" in which the mission may be carried out. System "states" are distinguishable conditions of the system which result from events occurring prior to and during the mission. For example, the condition in which all system hardware is functioning within design specifications is one state. The condition in which the system is completely inoperable due to hardware, personnel, or procedural failures is a state at the other extreme. The conditions of partial system operation due to defects of hardware, personnel, or procedures are represented by the intermediate system states. It should be evident that the system can make transitions from state to state during a mission. The time-line analyses performed in accordance with 5.3, 5.4 and 5.5 may have split the mission into a number of discrete time intervals during which different

functions are being performed and different portions of the system's hardware are being used. For each discrete time interval, a set of significant states appropriate to the function being performed during that interval must be defined.

The next step is to relate probabilities to each of the sets of significant states which are appropriate at the beginning of the mission. This array of probabilities is called the availability vector. For each succeeding time interval, an array of state probabilities is related to accountable factors. These probabilities are dependent or conditional on the effective state during the previous time interval. For example, where no repair is possible, a failure in one interval predetermines the possible states in the succeeding intervals. These arrays of conditional probabilities are called the dependability matrices.

A simplified method of analysis which is generally employed, defines the significantly different (effective) system states over the entire mission rather than for each discrete time interval. The array of state probabilities at the beginning of the mission still yields the availability vector. However, the dependability matrix contains the probabilities of the effective states throughout the mission conditional on the initial states.

The last step is the construction of the capability vector. This is an array of numbers which are a measure of the ability of a system to achieve the mission objectives; given the system condition(s) during the mission. This array of numbers (vector or matrix) specifically accounts for the performance spectrum of the system. A spectrum of possible mission results occurs, for example, when the accumulation of subsystem performance deviations, each within acceptable tolerances, results in a bomb drop being wide of the mark. In this case, there has been no specific subsystem malfunction, but a system malfunction (or performance degradation) due to the unlikely combination of within tolerance variations of the subsystem. There may, therefore, be a continuous spectrum of possible mission results, none of which is an unequivocal failure or success. The capability matrix represents the "worth" or "value" of each system state.

Each element of the matrix is the mission worth which accrues from carrying out the mission in a given effective state.

The basic analytical framework given above is not intended to be restrictive. This point is illustrated in the radar detection and tracking example of Volume II of the Task Group II report where the following variations on the basic model are illustrated:<sup>(3)</sup>

$$E_1 = \bar{A}' \bar{C}(0)$$

$$E_2 = \bar{A}' [C(0)] [D(30)] \bar{C}(30)$$

$$E_3 = \frac{E_2}{E_1}.$$

In the first variation, the system effectiveness ( $E_1$ ) is defined to be the probability that the radar will adequately perform initial detection of the target. In this case the dependability matrix reduces to unity since "mission duration" is measured from the point of initial detection, and  $\bar{C}$  applies to detection capability only (denoted by  $\bar{C}(0)$ ). In the second variation, the system effectiveness ( $E_2$ ) is defined to be the probability of initial detection and track for a period of thirty minutes. In this case, the elements of the detection capability vector  $\bar{C}(0)$  become the elements of a capability matrix  $[C(0)]$  are now combined with a dependability matrix  $[D(30)]$  and a new capability vector  $\bar{C}(30)$  which express the tracking capability of the radar for a period of thirty minutes. In the final variation, the system effectiveness ( $E_3$ ) is defined to be the probability of successful track, given initial detection. This conditional measure is the ratio of the two previously treated variations.

The intended flexibility of approach is further illustrated in the avionics example, which is Example A of Volume III of the Task Group II report, where the following series of effectiveness measures are illustrated,<sup>(4)</sup>

$$E_j^{(i)} = \bar{A}_j' [D]_j \tau_j^{(i)}$$

$$E^{(i)} = \prod_{j=1}^k E_j^{(i)}$$

$$E = \sum_{i=1}^m P_i E^{(i)}.$$

The first measure  $E_j^{(i)}$  treats the effectiveness of the  $j^{\text{th}}$  system function or subsystem in the  $i^{\text{th}}$  mode of operation in terms of the basic analytical model. The system effectiveness in the  $i^{\text{th}}$  mode of operation ( $E^{(i)}$ ) is then treated as the continued product of the  $E_j^{(i)}$  over the  $k$  subsystems (or functions) that collectively define the avionics system. Finally, the net effectiveness of the entire avionics system ( $E$ ) is the sum of the effectiveness of the system in each of its modes of operation  $E^{(i)}$  multiplied by the probability  $P_i$  of utilizing that mode of system operation, where  $m$  is the number of modes of operation.

The common elements in these variations are availability, dependability and capability. The precise manner in which they combine depends wholly upon the specific definition of system effectiveness which is to be considered.

Furthermore, the recommended basic expression is not intended to exclude simulation from consideration. It is generally acknowledged that the complexity of modern systems will frequently preclude a detailed pencil and paper treatment except as a first cut analysis. However, when simulation must be resorted to, it is recommended that the computer representation of the system should produce intermediate by-products which can be clearly identified as availability, dependability and capability.

The value of (7.4) construction of cost-effectiveness models lies in the ability to use the model to evaluate new concepts, to direct effort toward optimum systems, to evaluate the effect of enemy advances in technology, and to define meaningful research and development programs.

Since we are concerned here with quantitative methods, each system characteristic or variable must be represented by numerical measures. The questions of precision, accuracy, and consistency of measurement must be carefully examined, satisfactorily resolved, and presented in each study. The sub-models to be generated within an operational concept will not be independent; so the elements jointly involved will have to be examined for consistency from sub-model to sub-model.

The first step in the basic optimization process is to relate the variables used with each other and with the resources which are affected. These relationships must be expressed in such a manner that the variables and resources can be expressed in terms of the established cost-effectiveness criteria and measures. Development of relationships must be carried to the point where all resources and variables can be related to either a single common denominator, (usually dollars), or to a cost denominator (dollars) and an effectiveness measure. The relationships so developed are then expressed in model form which is essentially a mathematical, logical, or physical representation of the interdependencies between the variables, resources, and measures of effectiveness.

The WSEIAC reports discuss three basic types of cost models;

- profit model
- cost-effectiveness ratio model
- long term effectiveness ratio model.

The profit model is simply the application of the commercial concept of maximizing return on investment. This may be stated in terms of maximizing absolute return

$$\begin{aligned} P &= E - C \\ &= \text{value received (or expected)} \\ &\quad - \text{cost expended (or expected)} \end{aligned}$$

or in terms of maximizing rate of return

$$r = \frac{E - C}{C} .$$

The usefulness of either of these profit models is contingent on solution of the rather difficult problem of finding a common unit of measure for E and C. This has been done in the past by such arbitrary means as indexing each on a common scale (e.g., 0 to 100) or by relating E to value of targets killed, value of property defended, or protected, etc. However, such arbitrary scaling -- whatever the logic upon which it is based -- often leads to gross misunderstandings and frustrations on the part of those involved in the decision making process.

The rate of return profit model suffers from an additional difficulty. Under some circumstances the optimum (maximization) of a ratio function may occur at the origin. That is, one finds that the best system is no system at all!

The cost-effectiveness ratio model, as indicated by the name, is given by:

$$f_1 = C/E = \frac{\text{cost expended (or expected)}}{\text{value received (or expected)}}$$

or

$$f_2 = E/C.$$

Here it is desired to minimize  $f_1$  or maximize  $f_2$ .

This type of model has the advantage of providing a cost-effectiveness measure in natural terms. Thus, in terms analogous to transportation (cents per ton-mile, etc.), cost-effectiveness measures dollars per kill, etc. This type of model is, therefore, very useful in comparing alternative solutions to the same problem. On the other hand, we are again faced with the dilemma posed by ratio functions. One way out of this difficulty is to express  $f_1$  or  $f_2$  in an equivalent form using Lagrangian multipliers. Thus, we may seek to maximize E subject to a constraint on cost C.

For example, we attempt to maximize,

$$E + \lambda_c (C - C_0)$$

where  $C_0$  is a fixed budget and  $\lambda_c$  is called a Lagrangian multiplier.

Schedule may likewise be accounted for by means of Lagrangian multipliers. For example, during acquisition, we may maximize

$$E + \lambda_c (C - C_0) + \lambda_t (t_d - t_s)$$

where

$t_d$  = time required to develop a given level of  $E$  at a given cost  $C$

$t_s$  = fixed date of termination of development (constraint)

$C_0$  = fixed development budget (constraint).

Alternatively, we may seek to minimize cost  $C$  subject to a constraint on  $E$ . That is, we attempt to minimize the expression

$$C + \lambda_E (E - E_0)$$

where  $E_0$  may be interpreted as the minimum acceptable system effectiveness (constraint).

It should be noted that this approach does not require that the constraints be single valued. They may be stated as inequalities.

The long term cost-effectiveness model differs from the above cost-effectiveness ratio model only in that effectiveness is to be averaged over the entire life of the system. In general,

$$E = \frac{1}{t_0 - t_e} \int_{t_0}^{t_e} E[t] h[t] dt$$

where

$t_0$  = date of initial deployment of system

$t_e$  = date of system phaseout

$h[t]$  = the worth of a given  $E$  at any point in time between  $t_0$  and  $t_e$ .

$E$  = the effectiveness of the system at time  $t$ .

This model is subject to the same difficulties as the foregoing model, and in addition, it has the additional difficulties of requiring a "judgment function"  $h(t)$  and a knowledge of the future  $E(t)$ .

Clearly each of the above model types has its advantages and disadvantages. None is the perfect answer for all system evaluations. Each is useful on occasion. The choice of a particular model will depend upon the system and the type of question being asked. However, whatever the basic model type chosen, the formulation of a cost-effectiveness model should be in terms of a maximization or minimization process subject to constraints. This process is called "trade-off" studies in the common parlance of the industry. Trade-offs are those compromises made possible by a substitution among elements, values, or materials to secure a preferred value of a critical system characteristic.

Table V lists the areas which an analyst must consider in going from physical and engineering performance characteristics to a relationship between cost factors and effectiveness factors.

A typical cost estimating relationship is shown in Figure 7. Estimating relationships within a known technology or over a range of technologies is obtained by interpolating among data points developed during current or previous programs. However, if it is necessary to extrapolate to new performance levels, then the performance must be developed by technology and then related to cost. Figure 7 shows the effect of technological changes on performance-cost relationships and indicates that empirical data will describe the envelope of the relation.

Effectiveness parameters will be estimable from some set of system events. The identity of these events will be uniquely defined by 9.1, Specification of Parameter Estimation Methods, in conjunction with the 8.2, Specification of Test Methodology.

TABLE V  
POTENTIAL TRADE-OFF AREAS

| <u>RESOURCES</u>     | <u>VARIABLES</u>  | <u>ALTERNATIVES</u>                           |
|----------------------|-------------------|-----------------------------------------------|
| -Funds Available     | -Cost             | -Basic Concept                                |
| -Time Available      | -Weight           | · Manned Versus Unmanned                      |
| -Payload Capability  | -Payload Carried  | · Liquid Versus Solid<br>Rockets              |
| -Manpower and Skills | -Mission Length   | -System and Subsystem Type                    |
|                      | -State of-the-Art | · Battery Power Versus<br>Generation          |
|                      | -Time Required    | · Materials Choice                            |
|                      | -Reliability      |                                               |
|                      | -Safety           | -System and Subsystem<br>Configuration        |
|                      | -Maintenance      | · Redundancy                                  |
|                      | -Availability     | · Maintainability                             |
|                      | -Vulnerability    | · Hi-Reliability Versus<br>MIL Standard Parts |
|                      | -Survivability    | -Operational Modes                            |

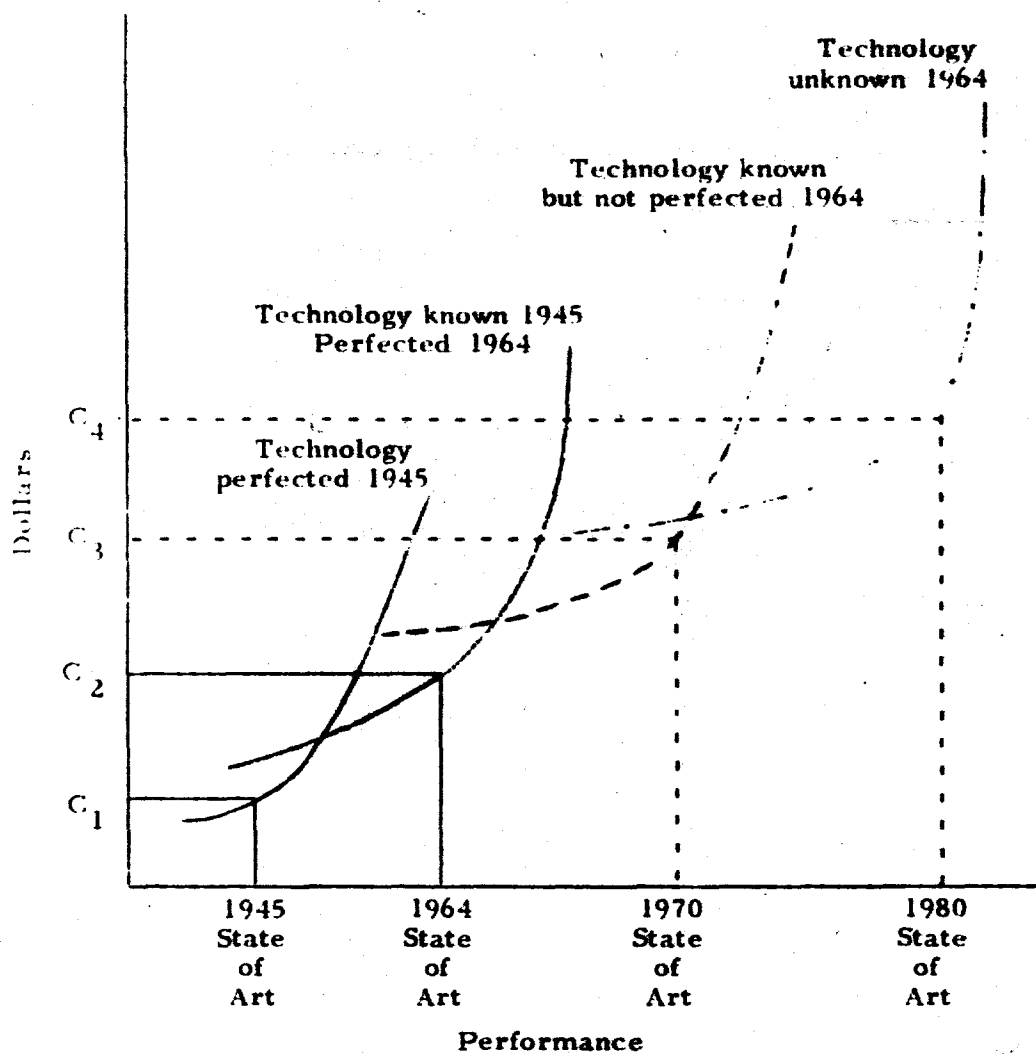


FIGURE 7. COST ESTIMATING RELATIONS BETWEEN A PERFORMANCE VARIABLE AND COST

I. BLOCK 8.0 DATA ACQUISITION

Planning for data acquisition requires careful attention to:

- 8.1 Specification of Data Elements
- 8.2 Specification of Test Methodology
- 8.3 Specification of a Data Collection System

There is no mystery attached to the 8.1 Specification of Data Elements. Effectiveness data elements (8.1.1) must be chosen such that they determine:

- the location of a system-significant event in space and time in such a way that the event can be uniquely related to:
  - concurrent events
  - immediately previous events.

The minimum information which is required to uniquely specify an event is:

- geographic location of the event (site number, base, depot)
- system location of the event (aircraft number, guidance subsystem, module, etc.)
- name of the event (checkout, change of status, problem encountered, apparent failure, flight, etc.)
- name of affected item (part number, drawer number, component type, etc.)
- time of the event (clock time and date)
- action taken (replace part number \_\_\_, repaired in place, performed checkout with TO number \_\_\_, etc.)
- results of action taken (successful launch, verification test, flight aborted, launch delayed "τ" minutes, etc.)

The key to an adequate data acquisition program is the determination of those events which are system significant. An event is only of significance if it contributes to the evaluation of a parameter of the system model. Thus, the determination of system-significant events hinges upon the parameter list (7.2) of 7.0 Model Construction.

The above logic was applied to the availability factor of effectiveness for an ICBM fleet in the technical addendum (Volume III) of the Task Group II Final Report.<sup>(4)</sup> The resulting data requirements were then used to judge the adequacy of the official Air Force data collection system (AFM 66-1), the SAC U-82, and the SAC U-86 data forms as illustrated in Table VI. They flunk.

The cost of the AFM 66-1, Maintenance Data Collection System (MDCS) is about 6.6 million dollars per year, as a conservative minimum. Surely, such a costly system should yield much more useful and more accurate information.

Clearly, some system such as the AFM 66-1 MDCS should be used to supply data for system effectiveness measurements. However, the AFM 66-1 MDCS, itself, is totally inadequate. This has been well documented (reference Task Group II,<sup>(2,3,4)</sup> Task Group III,<sup>(5)</sup> Klug Report, Parcel E).

The data collection forms of this system were originally designed to obtain maintenance data, not reliability or other effectiveness data. The recent attempts to use these forms for reliability and maintainability have failed. Recommended changes to the system, requested as early as 1961, arising from studies such as that at Oxnard Air Force Base, California, (documented in RAND Memorandum RM-3370-PR) have not been implemented.

In addition to having insufficient information, the data forms, themselves, are so poorly designed they encourage the generation of inaccuracies -- both in key-punching and in data-logging. The extent of these inaccuracies is unknown, but certain contractor studies show that they are on the order of ten per cent to forty per cent. Decisions based on such data should certainly be suspect. (It is pertinent to mention here that the current AFLC "error audits" and "error" percentages do not reflect data accuracy but, rather, block-entry accuracy.)

TABLE VI  
DATA AVAILABLE FROM CURRENT AF DATA REPORTING SYSTEMS

| Items of Informations                                              | U-82 <sup>1, 6</sup> | U-86 <sup>3, 7</sup> | AFM 66-1 <sup>7</sup>      |
|--------------------------------------------------------------------|----------------------|----------------------|----------------------------|
| Location (by site number and base)                                 | yes                  | yes                  | yes                        |
| Name of checkout                                                   | no <sup>2</sup>      | yes                  | no <sup>8</sup>            |
| Name of subsystem                                                  | yes <sup>4</sup>     | yes                  | yes <sup>4, 9</sup>        |
| Time and date of assignment to EWO                                 | yes                  | no                   | no                         |
| Time and date of entry to checkout                                 | yes                  | yes                  | date of completion only    |
| Time and date of each problem encountered in checkout              | yes                  | yes                  | problem <sup>10</sup> only |
| Description of each problem encountered in checkout                | yes <sup>12</sup>    | yes                  | yes <sup>10</sup>          |
| Date of bench test of rejected parts                               | no                   | no                   | date only <sup>5</sup>     |
| Results of bench test                                              | no                   | no                   | yes <sup>5</sup>           |
| Date of tear-down failure <sup>11</sup> analysis of rejected parts | no                   | no                   | no                         |
| Results of failure analysis <sup>11</sup>                          | no                   | no                   | no                         |

1 "by exception" reporting; i.e., only when condition takes site off alter

2 was removed from data system recently (November 1963). Is scheduled for return to data system when checkout SGC are detailed in -06 code books

3 reports countdown only

4 through Work Unit Code correlation only

5 available for recoverable items only

6 key punched for machine processing

7 not keypunched, or only partially keypunched

8 requires Support General Code of -06 Code and changes to TO-0020E-1

9 no Work Unit Code when checkout only

10 cannot correlate checkout AF TO Forms and resulting maintenance problem

11 can be directed by responsible AMA as a special task for problem areas

12 problem -- frequently cannot be correlated to checkout data.

The AFM 66-1 MDCS needs major changes; i.e., formats, key punching, method of tape record storage, response time, product outputs, feedback to bases, accuracy checks, checks on data output product useage. Perhaps only the concept itself should be retained; i.e., base maintenance logging data, base comptroller key-punching, forward to control agency, feedback to agencies needing such data.

These various problems coupled with the inflexibility to change of this official Air Force data system have caused many of the commands to establish separate data systems and forms piecemeal and for specialized purposes; e.g., SAC's U-82, ADC's proposed forms, AFSC's Form 258-5, and the like. The result today is that data, especially data relating to system effectiveness, is currently fragmented throughout the Air Force. No agency oversees the entire effort. In fact, the absence of a responsible agency to discharge this responsibility seriously hampers data collection efforts and wastes money. There is no means to resolve differences among commands, to see that data requested by one command and generated by another is, in fact, even used; no means to see that feedback to data collectors, especially on errors, is heeded and used to make the system more accurate; no means to see that valid data requests are processed and data given to agencies who need it to make the system more effective or to determine if it meets minimum acceptable requirements.

In addition to effectiveness data, it is necessary to obtain cost data if cost-effectiveness calculations/optimizations are to be accomplished. WSEIAC's remarks in this area are limited to pointing out that the 8.1.2 specification of cost data elements in the Air Force is currently not carried out with sufficient uniformity nor in sufficient detail. There must be uniformity in the major data categories, and the data must be kept in basic units so that it can be employed in analyses which require different viewpoints and constraints. Figures 8, 9 and 10 present the cost categories which must be considered in a cost-effectiveness analysis if it is to have the value desired.

It is abundantly clear that data collection in the Air Force is in need of substantial improvement if a system effectiveness/cost-effectiveness

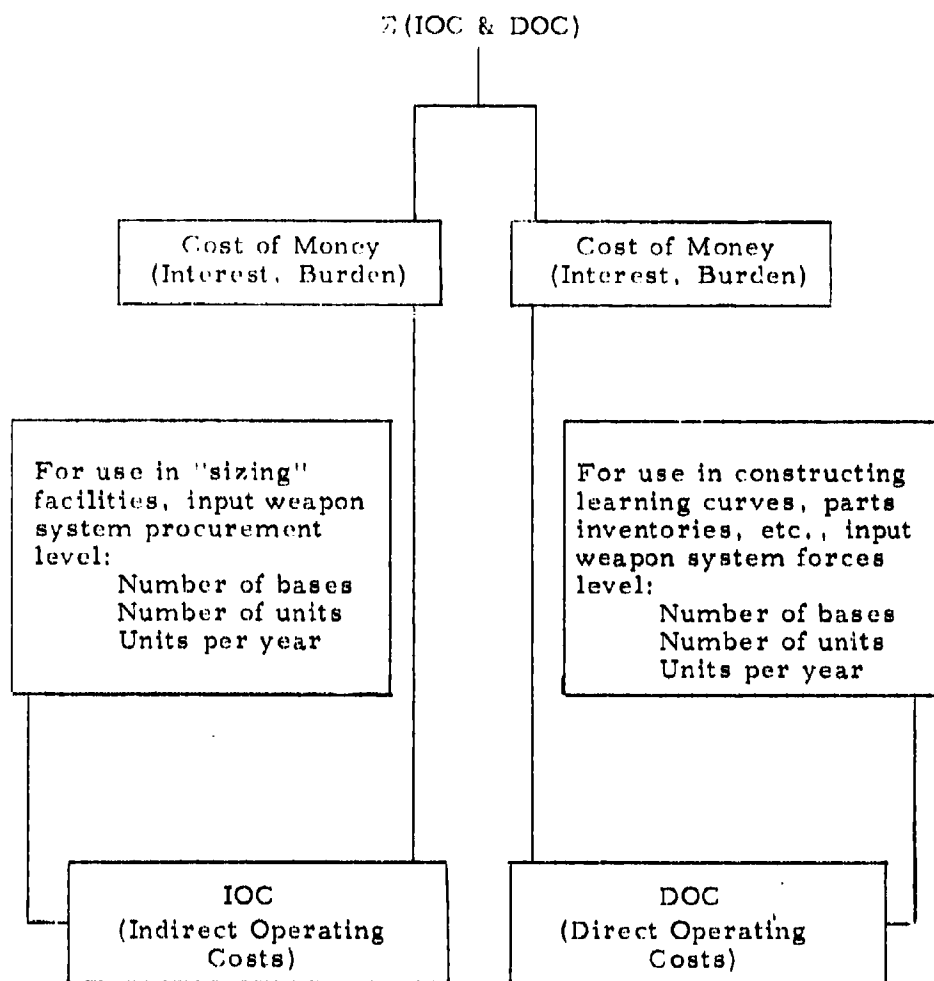
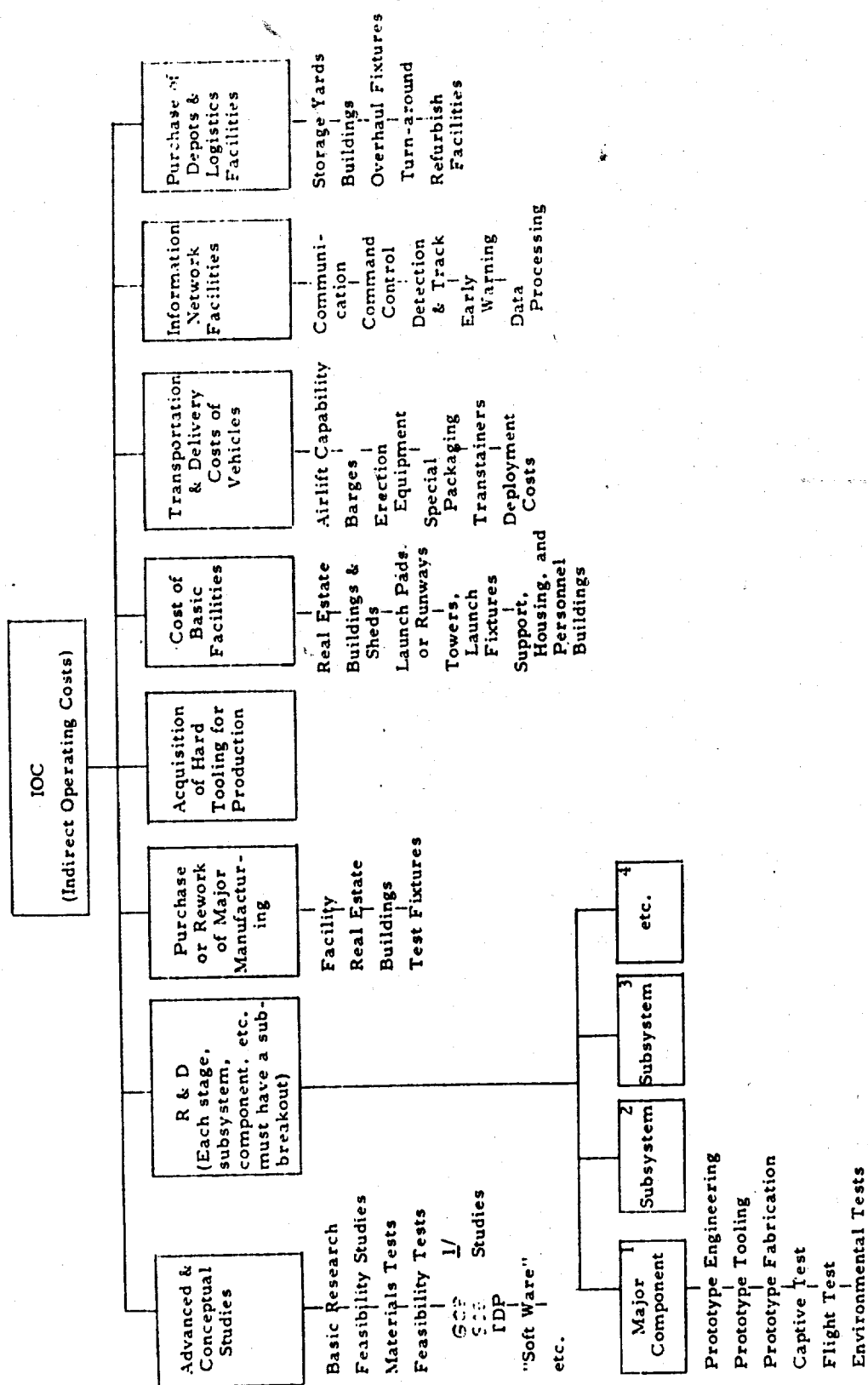


FIGURE 8  
COST BREAKOUT CHART FOR ESTIMATING CRITICAL RESOURCE UNITS  
REQUIRED TO DESIGN, DEVELOP AND OPERATE A SYSTEM



1/ GOR = General Operating Requirement  
 SOR = Specific Operating Requirement  
 TDP = Technical Development Plan

FIGURE 9  
 ASPECTS OF INDIRECT OPERATING COSTS

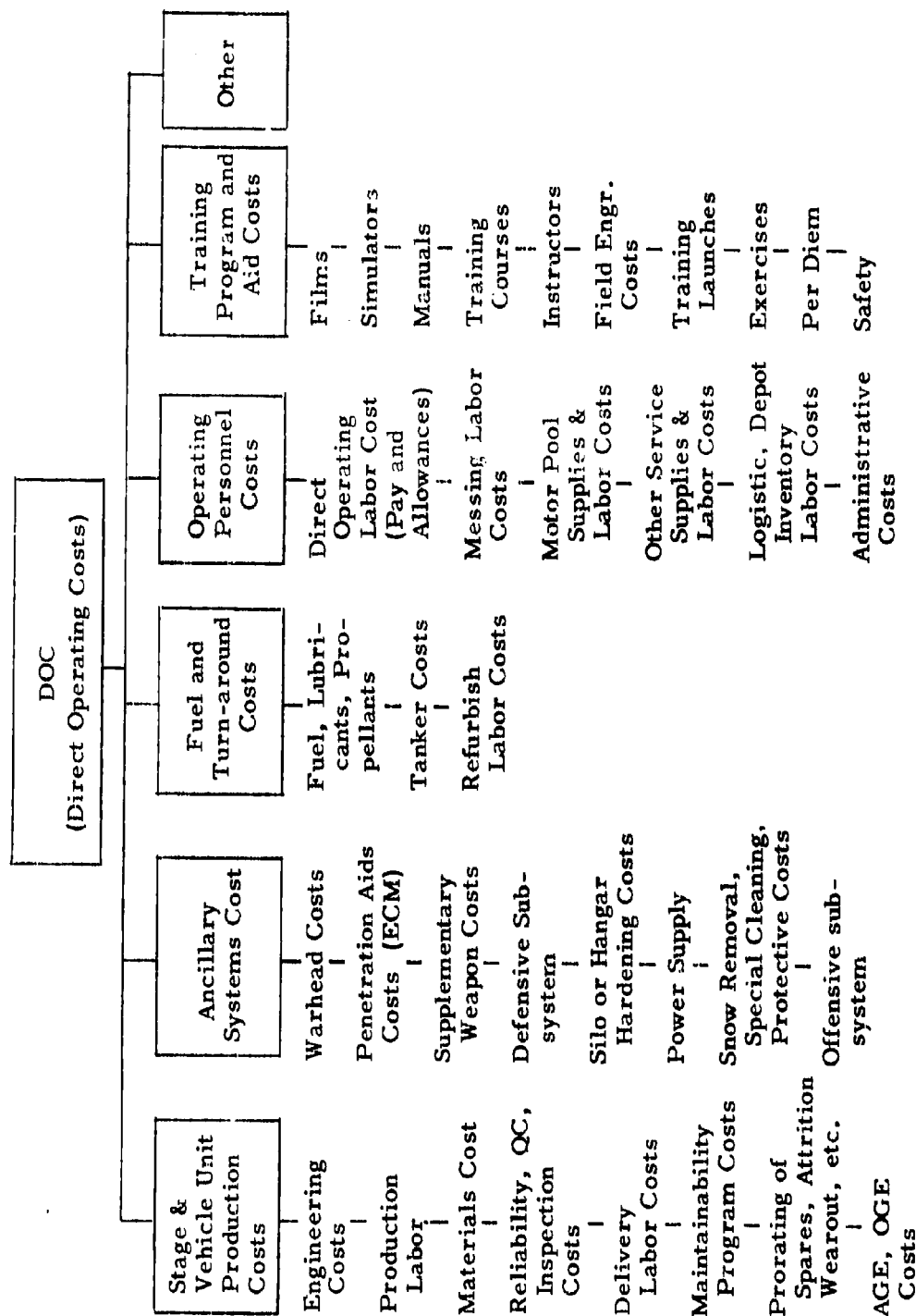


FIGURE 10. ASPECTS OF DIRECT OPERATING COSTS

program is to be implemented. Block 8.3 Specify Data Collection System of Figure 13 indicates those considerations which should receive attention in developing an adequate system cost and effectiveness data collection system. Briefly, they are:

- 8.3.1 specify administration
- 8.3.2 specify personnel
- 8.3.3 specify software
- 8.3.4 specify data preprocessing
- 8.3.5 specify data transmission

The word "data" is used in the 8.3 Specification of a Data Collection System in a broad context connoting a wide spectrum of information. It refers to any information, pertaining to the system, which is to be recorded and/or published. Data includes:

- Training Manuals
- Program Plans
- Management Summaries
- Cost Data
- Performance Data
- Information on Research Costs, Facilities Cost
- Engineering Drawings
- Maintenance Data
- Reliability Laboratory Data
- Test Data
- Progress Reports
- Operating Instructions

A data system is an organized methodology or process used to gather, store, retrieve, display, publish, and distribute the above data. For such a system to exist, it is necessary that an organization exist which is responsible for performing these functions, that that organization be manned, funded, and have sufficient equipment and authority to discharge its responsibilities. To accomplish its functions it requires a mechanized (computerized) system for data processing.

A system effectiveness data system is then, a system used to collect the data required to predict, measure, and evaluate system effectiveness. Clearly, it is concerned with cost data, reliability data, and maintenance data, as well as with other types of data. The data requirements are covered more thoroughly in Task Group II, Task Group III, and Task Group IV's reports, but still need refinement and coordination before they can be programmed into a mechanized system.

## J. BLOCK 9.0 DATA PROCESSING

The processing of data for purposes of providing effectiveness and cost-effectiveness calculations can be a large undertaking. Attention must be given to:

- 9.1 Specification of Parameter Estimation Methods
- 9.2 Specification of Administration
- 9.3 Specification of Personnel
- 9.4 Specification of Hardware
- 9.5 Specification of Software

The 9.1, Specification of Parameter Estimation Methods, is a crucial step involving

- 9.1.1 specification of effectiveness parameter estimation methods
- 9.1.2 specification of cost estimation relationships

"Parameter estimation" is defined here to mean the specific analytical techniques used to reduce raw data. The specific methods used depend upon:

- the nature of the quantity being estimated
- the control which can be exerted over the physical mechanisms which generate the data
- the format of data collection.

The 9.1.1 specification of effectiveness parameter estimation methods is simplest when a control population is available. The literature covers this situation quite thoroughly. On the other hand, when data are fortuitously collected under a variety of environments (as is the usual case with field-generated data) specifying suitable parameter estimation methods is more difficult. This problem was given some consideration by Task Group II<sup>(4)</sup> but much remains to be done in this area.

Section V of Volume II of the Task Group IV final report considers the 9.1.2 specification of cost estimating relationships in some detail.<sup>(7)</sup> A particular methodology is outlined and the current AFSC format for recording cost estimating relationships is given.

The areas of 9.2, Administration; 9.4, Hardware; and 9.5, Software, are treated extensively in the Task Group III final report.<sup>(5)</sup>

**K. BLOCK 10.0 SPECIFY SCHEDULE**

Schedule is viewed as a constraint (requirement). The manner in which it can be explicitly accounted for was discussed in 7.0 Model Construction.

**L. BLOCK 11.0 MODEL EXERCISE**

There are two principal uses of models:

- evaluation
- prediction.

Evaluation provides:

- surveillance of current system status against quantitative system requirements
- feedback upon the efficacy of the management decision and program control process
- a means of determining system weaknesses or potential problem areas
- a point estimate of system effectiveness which includes all pertinent factors within a uniform framework.

Prediction provides decision aids through:

- comparative (cost-effective) prediction/evaluation of competing
  - system configurations
  - problem solutions
- calculations of the effects of risk and uncertainty expressed as
  - confidence levels
  - parameter variation studies
  - changing requirements analysis.

The use of a system model involves eight steps:

- 11.1 perform model checks
- 11.2 calculate FOM's

- 11.3 do trade-offs within constraints
- 11.4 compare calculations with standard of reference
- 11.5 calculate parameter sensitivity curves
- 11.6 calculate risk
- 11.7 calculate effect of uncertainty
- 11.8 interpret runs.

The purpose of 11.1 Perform Model Checks is to test the basic structure of the model.

This consists of a set of checks on:

- assumptions
- adequacy
- representativeness
- risk and uncertainty
- validity

Assumptions All assumptions required for the model should be explicitly stated and, if possible, supported by factual evidence. If no such evidence exists, it is advisable to state the reason for the assumption (e.g., mathematical expediency) in order to indicate the degree to which the assumptions will require further justification, and to pinpoint the areas in which errors might be introduced.

Adequacy A model must be adequate in the sense that all major variables to which the solution is sensitive are quantitatively considered. Many of these variables will have been preselected. Through manipulation of the model, some of the variables may be excluded or restricted, and others may be introduced.

Representativeness Although no model can completely duplicate the "real world," it is required that the model reasonably represent the true situation. For complex problems, this may be possible only for sub-parts of the problem, which must be pieced together through appropriate modeling techniques. As an example, analytic representation may be possible for various phases of a complex maintenance activity. The outputs from these analyses may then be used as inputs to a simulation procedure for modeling the complete maintenance process.

Risk and Uncertainty The various types of unknowns involved in the problem cannot be ignored, nor can they be "assumed" out; they must be faced squarely. There may be technological uncertainties involved with some of the system alternatives, operating uncertainties involved with planning and carrying out the mission, uncertainties about enemy strategy and action, and statistical likelihoods governed by the laws of chance (referred to as risk). The simplest approach on uncertainties is to make "best guesses," but this may lead to disastrous results, since the probability of guessing correctly for every uncertainty is quite small. For cases involving statistical likelihood, functions-of-random-variables theory or such procedures as Monte Carlo techniques may be used. For the other types of uncertainties, the general approach is to examine all major contingencies and compute resultant cost-effectiveness parameters.

Validity It must be recognized that models will not be exact replicas of the "real world." Accordingly, they should not be used blindly. Portions of every model are usually common to previously used models or can be related to quantitative knowledge of trends available from past experience. The model is validated by checks in as many familiar regions as possible. The model is also checked for sensitivity of its output to changes in its basic structure. These sensitivity checks are made in all areas where simplifications have been made from the "real world" case or where anomalies have resulted from the validation checks.

Certain questions will disclose weaknesses that can be corrected:

- Consistency - are results consistent when major parameters are varied, especially to extremes?
- Sensitivity - do input-variable changes result in output changes that are consistent with expectations?
- Plausibility - are results plausible for special cases where prior information exists?
- Criticality - do minor changes in assumptions result in major changes in the results?

- **Workability** - does the model require inputs or computational capabilities that are not available within the bounds of current technology?
- **Suitability** - is the model consistent with the objectives; i.e., will it answer the right questions?

Given that the structure of the model has been verified, the figures of merit (FOM) may then be calculated (11.2), and trade-off studies made within constraints (11.3). The object of trade-off studies is system optimization.

### 1. OPTIMIZATION

If the model is analytic, the technique of Lagrangian multipliers may be employed. This technique is useful when well defined analytical relationships exist among the variables, and when the constraints are expressly stated as either single valued requirements or inequalities. Alternative techniques are preferable when the relations among the variables are empirical, discontinuous or discrete. For example, when a finite number of discrete alternatives exist, optimization would ordinarily be accomplished by the straight forward procedure of direct comparison of the calculated costs and predicted effectiveness of each alternative. (7, 8)

When the data is empirical, as opposed to analytical, graphical techniques will usually prove to be more useful and are particularly useful when the constraints are given as a bounding range of acceptable values. Evaluation of alternatives in this case may be treated by the methods described in Section VIII of Volume II of the Task Group IV Final Report.

In addition to the above techniques, there are a number of others available. Among the more common are:

- marginal analysis
- dynamic programming
- simple maximization
- Pontryagin's maximum principle
- linear programming
- calculus of variations

- method of steepest ascent
- "minimax principle" of the theory of games

The WSEIAC has not given an illustration of all these techniques, but has chosen to limit its examples to illustrations of those methods which are simple to grasp, easy to exploit, and have a fairly wide application to reality, namely:

- exhaustion of feasible alternatives
- graphical techniques
- simple maximization
- dynamic programming
- Lagrangian multipliers.

The ultimate output of the trade-off analyses is a system configuration with a certain numerical value of effectiveness. Model exercise is not complete until this value has been compared to the quantitative system requirements (SOR) or other standard of reference (11.4); a parameter variation analysis (11.5) has been made; risk (11.6) and uncertainty (11.7) have been calculated and an interpretation of the results (11.8) has been accomplished.

## 2. PARAMETER VARIATION ANALYSIS

The object of a parameter variation analysis is to show the sensitivity of system effectiveness/cost-effectiveness to changes in:

- system quantitative requirements, and
- system variables.

In general, the results of such analyses are given graphically. For example, quite simple models may be used in investigating the gross effects of alterations in system support through parameter variation studies. Consider a subsystem which is periodically inspected every  $T_s = 60$  days. Suppose that the point estimate of the availability is 0.57 based upon the assumption that test coverage during the inspections is complete ( $\lambda_u = 0$ ). The effect of having incomplete test coverage ( $\lambda_u \neq 0$ ), and of varying the inspection interval constitutes a parameter variation study. Figure 11 illustrates the results of such a study for this hypothetical system. (The

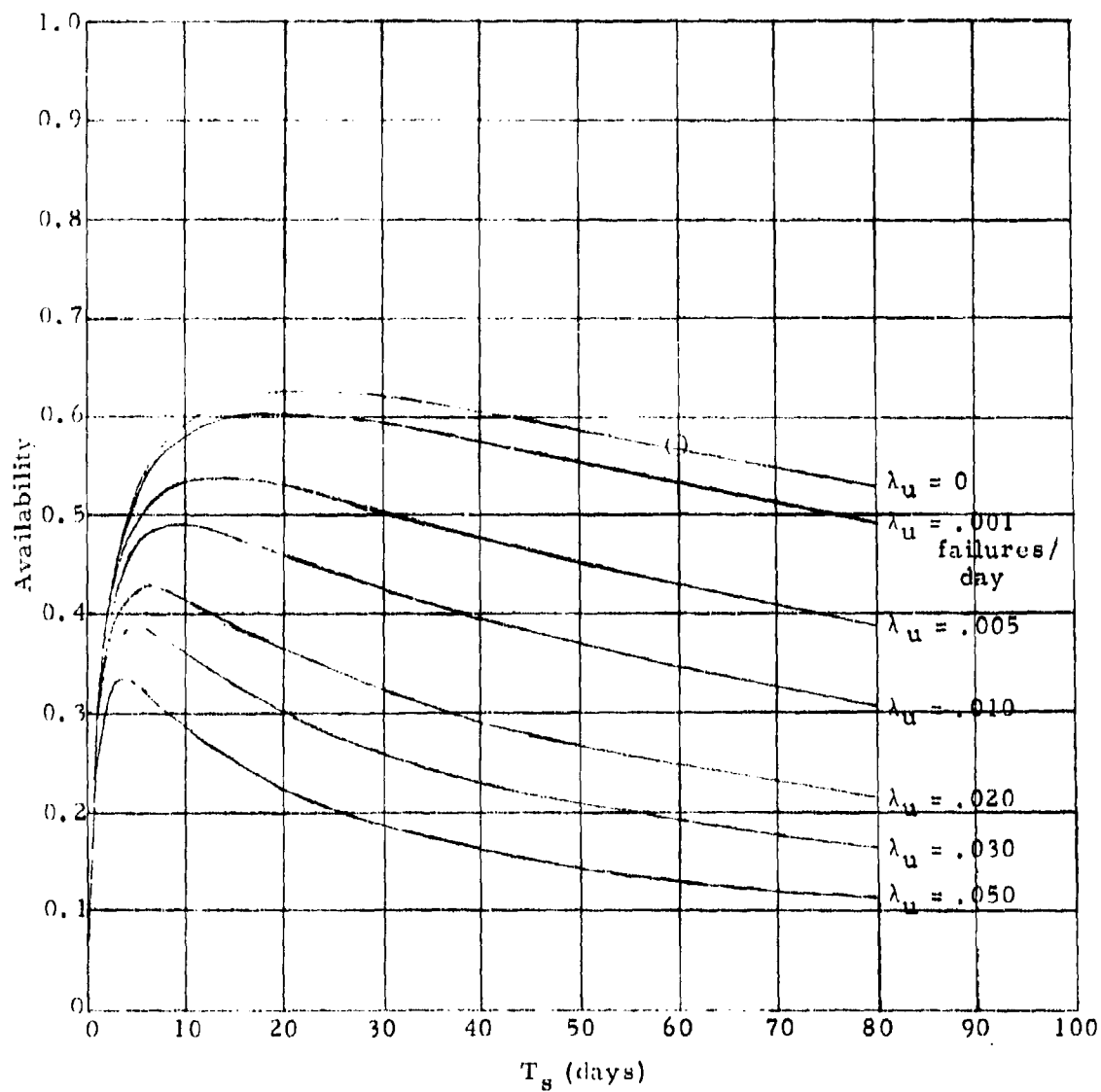


FIGURE 11  
 VARIATION OF AVAILABILITY WITH  
 CHECKOUT FREQUENCY AND TEST COVERAGE

point estimate is circled.) Two conclusions may be drawn from the graph:

- If it is consistent with manning levels, the inspection period should be reduced from 60 to 20 or 30 days; given that test coverage is complete ( $\lambda_u = 0$ ).
- If test coverage is not complete ( $\lambda_u \neq 0$ ), resulting in as little as one undetectable failure every 100 days ( $\lambda_u = .010$ ), the proper inspection interval is quite critical (6 - 15 days) and the true availability cannot exceed 0.49.

This analysis suggests two simultaneous actions with respect to this subsystem:

- reduce the inspection interval, and
- analyze the test procedures against the hardware to gain assurance that  $\lambda_u = 0$ .

This type of parameter variation analysis is, of course, most useful during Category II and Category III operations.

At the other end of the spectrum of parameter variation studies is the question of the effect of a proposed improvement on guidance accuracy. In this case interest is in the change in unit kill probability ( $P_k$ ). A general normalized curve is shown in Figure 12 where  $P_k$  is the probability of target destruction, given impact and detonation with proper yield in the target area.  $R_L$  is the lethal radius for the weapon and  $\sigma$  is the standard deviation of the accuracy of delivery. The improvement in  $P_k$  may be read directly from this curve for given values of  $R_L/\sigma$ . For example, suppose the current  $P_k = 0.4$  (i.e.,  $R_L/\sigma = 1$ ), and the proposed accuracy improvement is predicted to yield  $R_L/\sigma = 1.75$  leading to a predicted  $P_k = 0.8$ . A decision as to the worth of this change as compared to buying more weapons can be obtained using Figure 13 where we see that three weapons with  $P_k = 0.4$  equals one weapon with  $P_k = 0.8$ , or two weapons with  $P_k = 0.8$  are worth six weapons with  $P_k = 0.4$ .

### 3. INTERPRETATION OF RESULTS

During and after the accomplishment of the cost-effectiveness

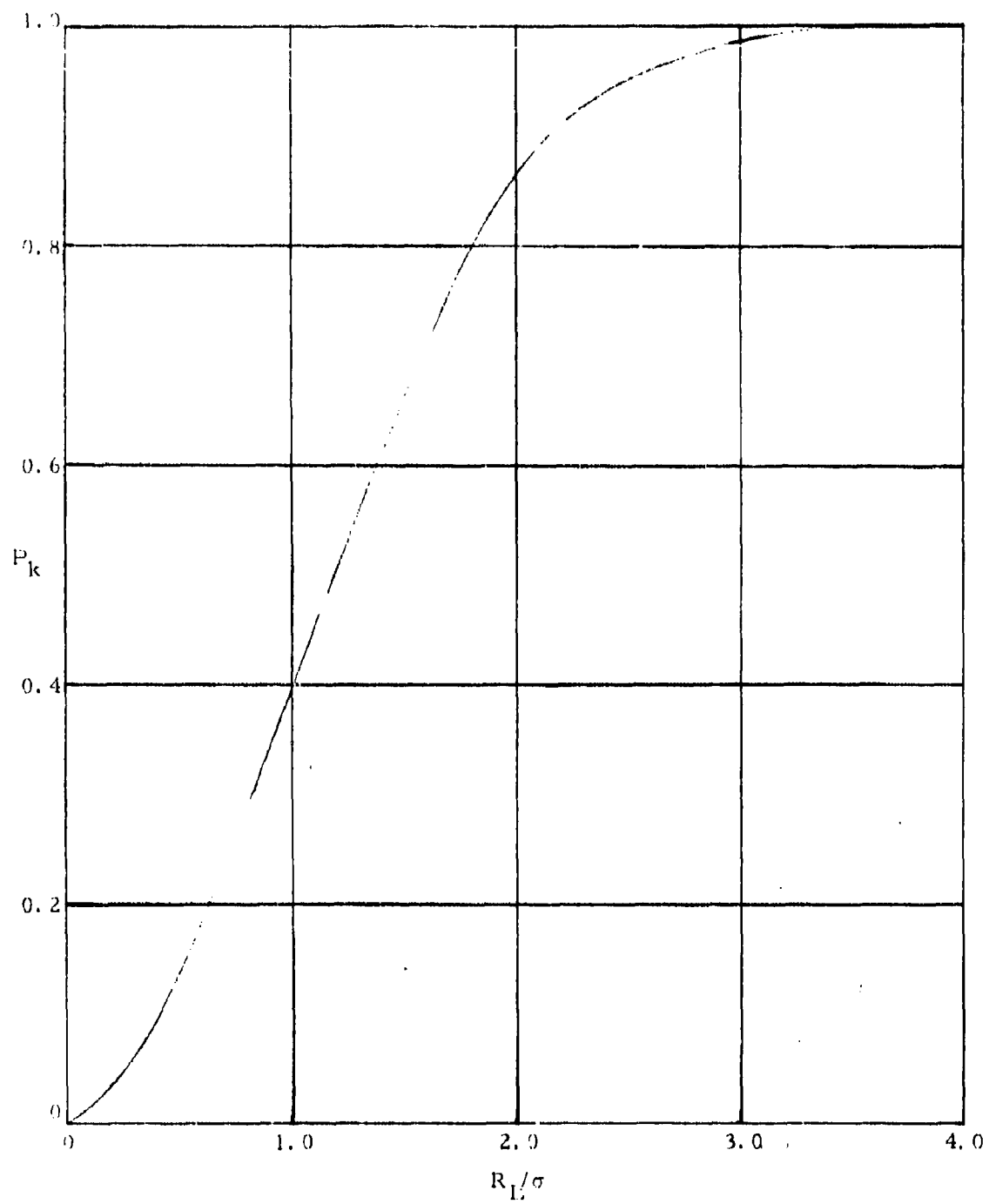


FIGURE 12. VARIATION OF UNIT KILL PROBABILITY

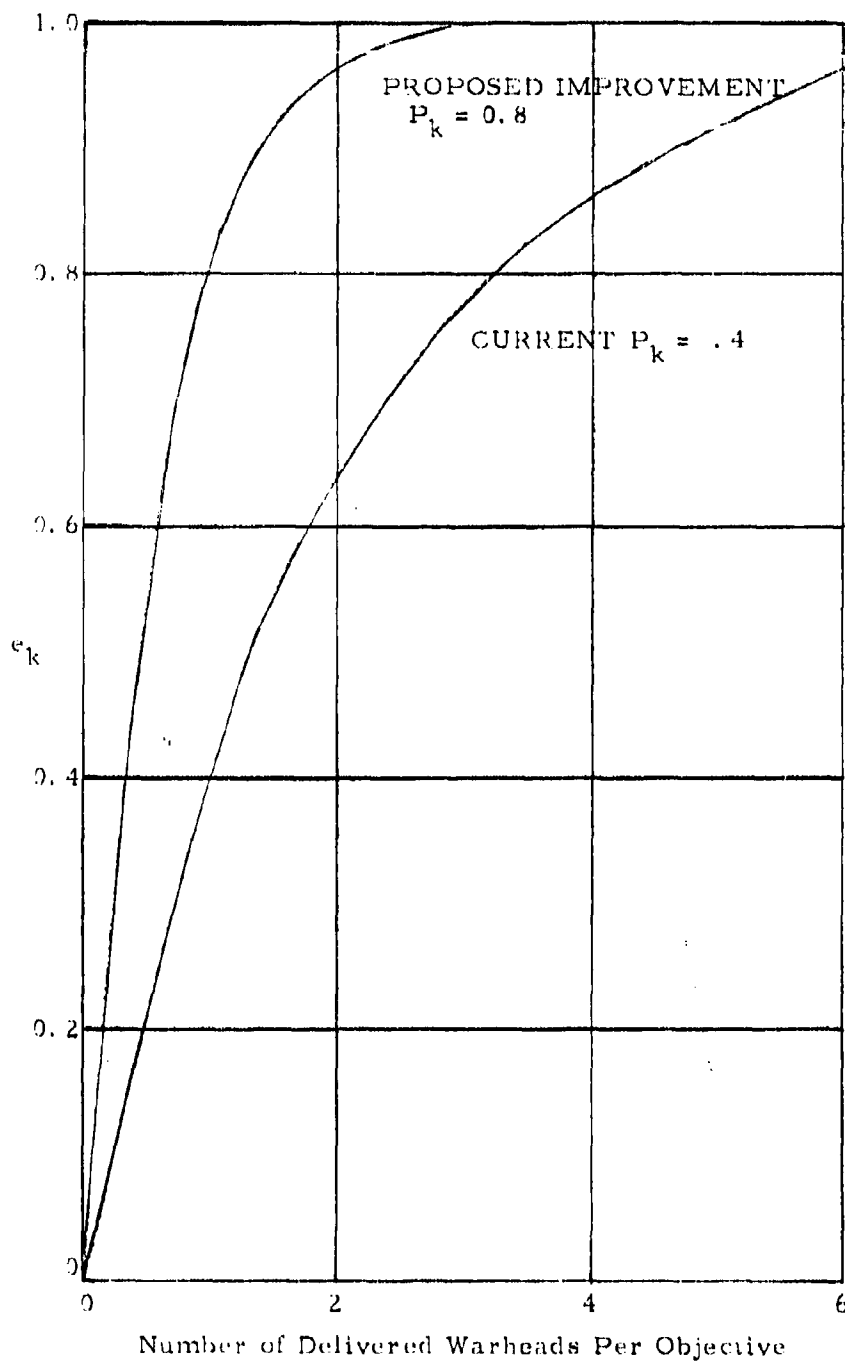


FIGURE 13. VARIATION OF EXPECTED KILL AS A FUNCTION OF THE NUMBER OF DELIVERED WARHEADS

analysis, the results of the study must be interpreted (11.8) in terms useful for the decision process. Of particular importance is the sensitivity of the results (i.e., in terms of cost-effectiveness measures) to variations in the input data. Thus, if the cost-effectiveness measure varies greatly with some design parameters, the decision process must consider carefully the uncertainty and the price paid by failure to achieve a design goal.

Interpretation is particularly difficult due to the usual communication problems among people of differing backgrounds and interests. This difficulty is amplified by the nature of qualifying statements which must be made concerning cost-effectiveness results due to risk and uncertainty and related result sensitivity.

The cost-effectiveness indices derived from a given set of input data used in studies and models of the type described here are measures of "goodness" or "badness" of a particular system or system configuration. The usefulness of the indices, then, depends on the validity of the model and the accuracy of the input data. But even though a particular submodel may represent reality only on a gross basis, or a particular piece of input data may be only a gross estimate of reality, the resulting index may still deserve confident consideration as a measure of goodness. The key is the sensitivity of the result to such gross representations. In sensitive areas associated with risk or uncertainty, "warning flags" must be attached and some idea of upper and lower bounds for the measure should be given. These warning flags can be obtained from parameter variation studies which will show the sensitivity of the model in the area of the uncertainty. Such sensitivity checks are needed since the output of a cost-effectiveness optimization study is used to support program decisions. Sensitivity checks are intended to determine the effect of uncertainty in the output data on the decisions involved. Three fundamental types of sensitivity checks will generally be applicable to the results of most cost-effectiveness studies. They are:

- sensitivity to basic system or mission requirements,
- sensitivity to uncertainties in estimated or extrapolated data, or
- validity of simplifying assumptions or arbitrarily fixed variables.

The basic steps involved in a sensitivity analysis are:

- An estimate or guess should be made as to the possible numerical range of uncertainty involved. Per the definition of uncertainty outlined in the previous sections, it should be recognized that such estimates or guesses will generally be unsupported by any data or background information. They are usually a matter of judgment.
- Using both the maximum and minimum values of the range, the optimization analysis or necessary portions thereof, should be rerun. The results of the nominal and extreme values can then be compared as required to determine whether decisions which would have been derived from the nominal analysis would be altered if the extreme values were believed.
- If it becomes apparent that the possible range of uncertainty does have significant effect on output decisions, steps should be taken to reduce the range of uncertainty, through either improvements in input data or testing for more or better data, improved analysis techniques or preparation of estimates at a lower level. In general, experience with this type of analysis has shown that only a small percentage of study inputs involving a range of uncertainty will be such that this range of uncertainty will influence output decisions. As an alternative, there are some situations where the basic design of the system can be altered in such a manner that the system is no longer sensitive to the estimated range of uncertainties. If it is not possible to remove the effects of the uncertainty range on the decisions involved, this effect should be shown in visible or parametric form along with analysis results.

If they are to be of value, the results of cost-effectiveness studies must be given in terms which are meaningful to those who make decisions. Thus the

analysts should appreciate the problems of communication with a broad spectrum of people including design engineers, company managers, military managers, military planners and, sometimes, congressmen and the general public.

In interpreting the results of these studies, it must be remembered that the state-of-the-art, resource constraints, political and military thinking and philosophy, enemy posture, etc., are in a constant state of flux. Thus, these results should not become associated with hard, fast, unchanging rules. A current finding that a reliability of 0.9 is best for a particular component should not become permanent dogma. The results should never be the basis for hindering research. Rather, they should provide guidelines for further exploration or tests designed to yield more fruitful information on which to base decisions.

The limitations of cost-effectiveness studies have already been suggested in the foregoing paragraphs. The reader should bear in mind that, whatever shortcomings or dangers may be associated with analytical studies such as these, decisions based on intuition, experience which has not been thoroughly analyzed, or a sample of personal opinions (bone feelings) are certainly less defensible and more subject to omissions of important factors. One would not build a bridge by intuitive design, overlooking sound structural engineering practice; yet many unknowns exist in regard to material mechanics and random loading behavior of structures.

Although, in a sense, statements on limitations of cost-effectiveness analyses may be regarded as platitudes, we present some of them here as reminders.

- Cost-effectiveness indices cannot be meaningful unless derived from a model which represents the "real world" fairly closely. Reality should not be buried under mountains of detail nor does great detail, by itself, create reality in a model.
- It must be remembered that cost-effectiveness analysis is an

iterative process. Early results should not be permitted to create such a lasting impression (favorable or unfavorable) as to lead one to ignore the results of later refinements. This can lead to disillusionment on the part of all concerned and, later, to abandonment of a valuable tool.

Cost-effectiveness analysis can never replace good engineering and management practice. It should be regarded as a supplementary tool to provide meaningful information. Final decisions must still be based upon sound judgment. This must be particularly emphasized since too many political, psychological (e. g., an individual's drive to solve a particular problem), prestige value, and other factors are not considered in a satisfactory manner at this time in such analyses.

When results are sensitive to factors associated with high degrees of risk or uncertainty, "warning signs" must be posted. The results must then be used judiciously in making decisions.

In much of what has been said in the foregoing, there is an obvious attempt to build up the importance of cost-effectiveness consciousness. Considerable emphasis has been placed on developing models for obtaining cost-effectiveness indices and optimization thereof. However, it must be remembered that these do not provide a final answer. They do provide guidelines, but judgment must still play a large part.

Perhaps, this is best expressed by Dr. Alain Enthoven's statement<sup>4/</sup>: "Do judgment and experience have no place in this approach to choice of weapon systems and strategy and design of the defense programs? Quite the contrary. The statement that the issue is judgment versus computers is a red herring. Ultimately all policies are made and all weapon systems are

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<sup>4/</sup>From a lecture, "Decision Theory and Systems Analysis," delivered during the Distinguished Lecture Series, sponsored by the Board of Trade Science Bureau, Washington, D. C., December 5, 1963.

chosen on the basis of judgments. There is no other way and there never will be. The question is whether those judgments have to be made in the fog of inadequate and inaccurate data, unclear and indefinite issues, and a welter of conflicting personal opinions, or whether they can be made on the basis of adequate, reliable information, relevant experience, and clearly drawn issues. The point is to render unto computers the things that are computers' and to judgment the things that are judgment's. In the end, there is no question that analysis is but an aid to judgment and that, as in the case of God and Caesar, judgment is supreme."

Thus, although there are limitations in the modeling process used to obtain cost-effectiveness indices, it must be remembered that this approach allows us to:

- organize and set into proper perspective the many alternatives of the problem;
- establish many "if-then" statements, pertaining to the alternatives of the problem;
- properly evaluate data uncertainties;
- examine many cases quickly which would require years of simulated combat to test; and
- explore systematically those cases which cannot be tested (you cannot go to war to test system effectiveness).

## BLOCK 12.0 PREPARE MANAGEMENT SUMMARY REPORTS

The 12.1 Specification of Content and 12.2 Specification of Format of management summary reports has been given careful consideration by the WSEIAC. Summary reports should contain:

- system quantitative requirements,
- current status,
- resources (remaining),
- trends,
- summary of problem areas,
- optimum (re) allocation of resources, and
- risk and uncertainty qualifications.

The format suggested is:

- trend line charts by system and subsystem in graph form showing risk and uncertainty  
backed up by
- three levels of tabular (matrix) detail  
and
- variational studies in graph form with risk and uncertainty shown<sup>5/</sup>.

## BLOCK 13.0 DECISION PROCESS

The WSEIAC viewpoint is that cost-effectiveness prediction is the focal point which provides management a perspective relationship between system status, available resources, constraints, and system quantitative requirements. The 12.0 Management Summary Reports provide management

- a summary of current (or predicted) status
- a summary of current (or predicted) resources
- a summary of current (or predicted) trends
- a summary of current (or predicted) problem areas

In addition, and in response to management initiative and query, the summary reports will contain

- the predicted consequences of possible alternative actions

and

- a gauge on the effects of risk and uncertainty.

Thus the direction that the 11.0 Model Exercise takes and the contents of the 12.0 Management Summary Reports directly reflect the tentative courses of action postulated by management. Not only does the ultimate responsibility for decision rest with management, but so also does the vital activity of posing the proper questions. Thus, cost-effectiveness prediction is a dynamic process which cannot occur without active management participation.

In spite of the catalytic role played by management, the 13.0 Decision Process, as such, has not been discussed by the WSEIAC. This is not an oversight, but a recognition of the lack of information. Formal effectiveness/cost-effectiveness prediction of the scope envisioned by the WSEIAC is without precedent. Implementation of the WSEIAC recommendations will certainly have an impact on current management decision processes. Decision processes will tend to become more formalized. The use of formal decision algorithms will become more wide spread.

It is a strong recommendation of the WSEIAC that a study be instigated to:

- clearly define the management uses of models, and
- develop decision algorithms consistent with the WSEIAC effectiveness/cost-effectiveness concepts.

Unless the outputs or final results of the cost optimization study can be placed in a form suitable for support of program decisions, the application of optimization principles becomes only an academic exercise. The type of decision support outputs which can be generally derived from the optimization technique are:

- definition of design and mission associated with the optimum point;
- criteria for evaluation and decision on future improvement alternatives; and
- parametric data for use in studies of other systems.

The basic optimization techniques described here involve incorporation of alternative approaches up to the optimum or to a resource cut-off point, whichever occurs first.<sup>(7)</sup> Inherently this approach is such that a definition of the configuration, mission and other scenario associated with the optimum point is readily determined, thus leading directly to 3.2 Configuration Documentation.

As the program progresses through Definition Phase and through its operational life, the description of alternatives (3.1) involved in the optimization process will become increasingly definitive and, in turn, the definition of the system corresponding to the optimum point will become more firm (3.2). In addition to system configuration definition, there are a number of other natural by-products of the optimization, such as: reliability and maintainability estimates, required number of operational units, etc. In short, it is possible, during successive iterations of the cost-effectiveness analysis, to determine those elements that significantly influence effectiveness and cost which are within the scope of the decision-making process.

It must be recognized that in the time period following completion of an optimization analysis, further system improvement alternatives will be considered for incorporation. The scope and complexity of an over-all system optimization analysis are generally such that it is undesirable to rerun the entire study each time such an improvement alternative is to be considered. As a result then, it is generally desirable to derive evaluation models and criteria from the optimum point and the resource relationships accompanying this point, in such form that future improvement alternatives can be evaluated somewhat independently of the over-all system analysis. There is, admittedly, an implicit danger in following such an approach in that when a large enough number of such alternatives have been incorporated into the system, the original optimization analysis becomes invalid, thus admitting the possibility of erroneous decisions. Determination of the circumstances and/or frequency under which the total optimization must be reiterated is a matter of individual judgment. General guidelines for formulation of evaluation criteria for future improvements are:

- It is desirable to issue such criteria in a form that can be utilized by an individual designer.
- The form must be such that a single criteria or cut-off is used. Thus, supporting data and relationships must be provided so that all variables and resources which are involved in future evaluations can be related in terms associated with the selected criteria.

#### **BLOCK 14.0 IMPLEMENT DECISION**

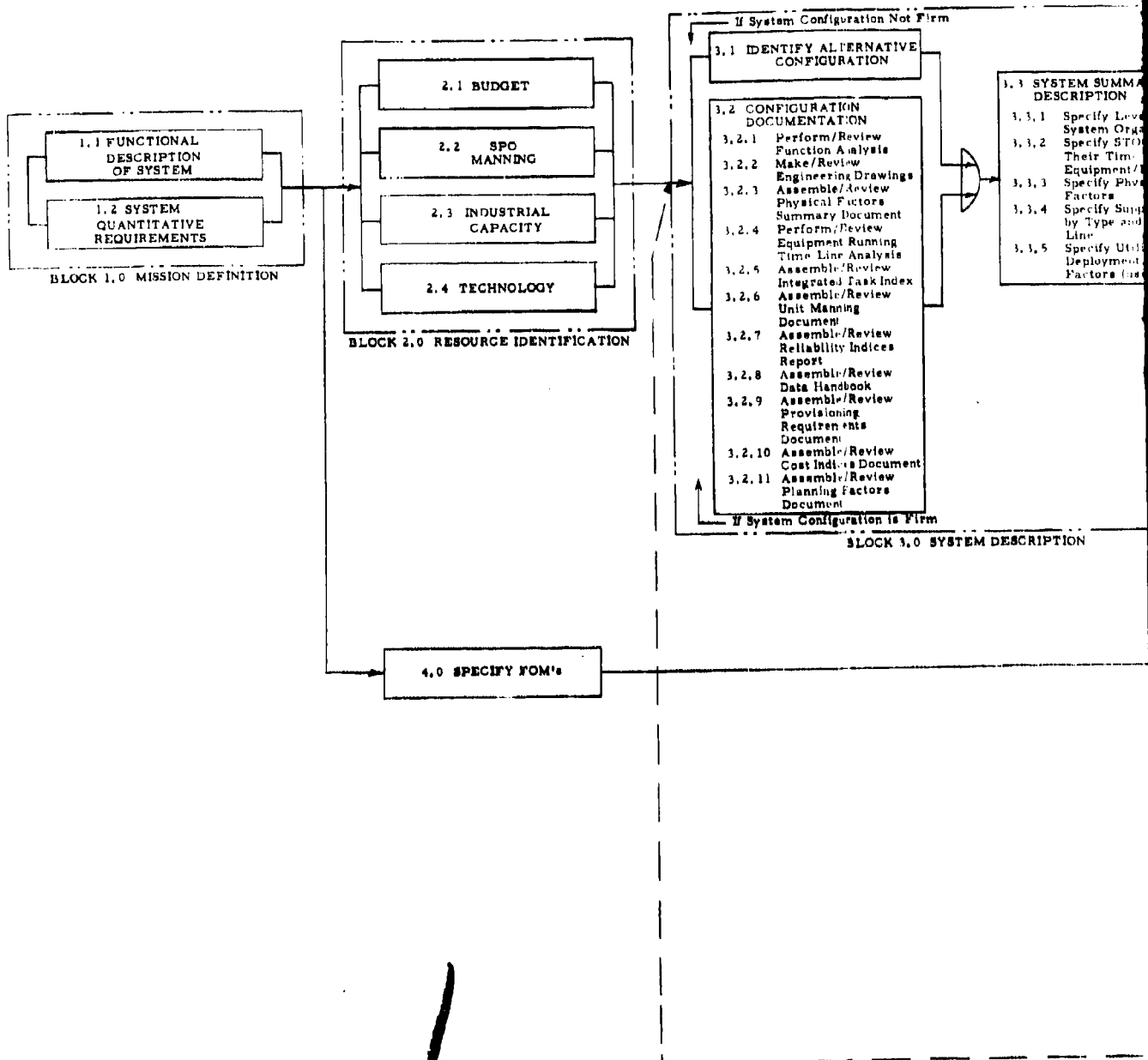
Implementation of decisions resulting from cost-effectiveness analyses is no different from implementing a decision from a design review, a schedule change or other significant program event. The block is included because it is an essential step in closing the loop and without which the model results and decisions alone are meaningless. The Task Group IV report contains pertinent discussion on management assurance activities during program surveillance.

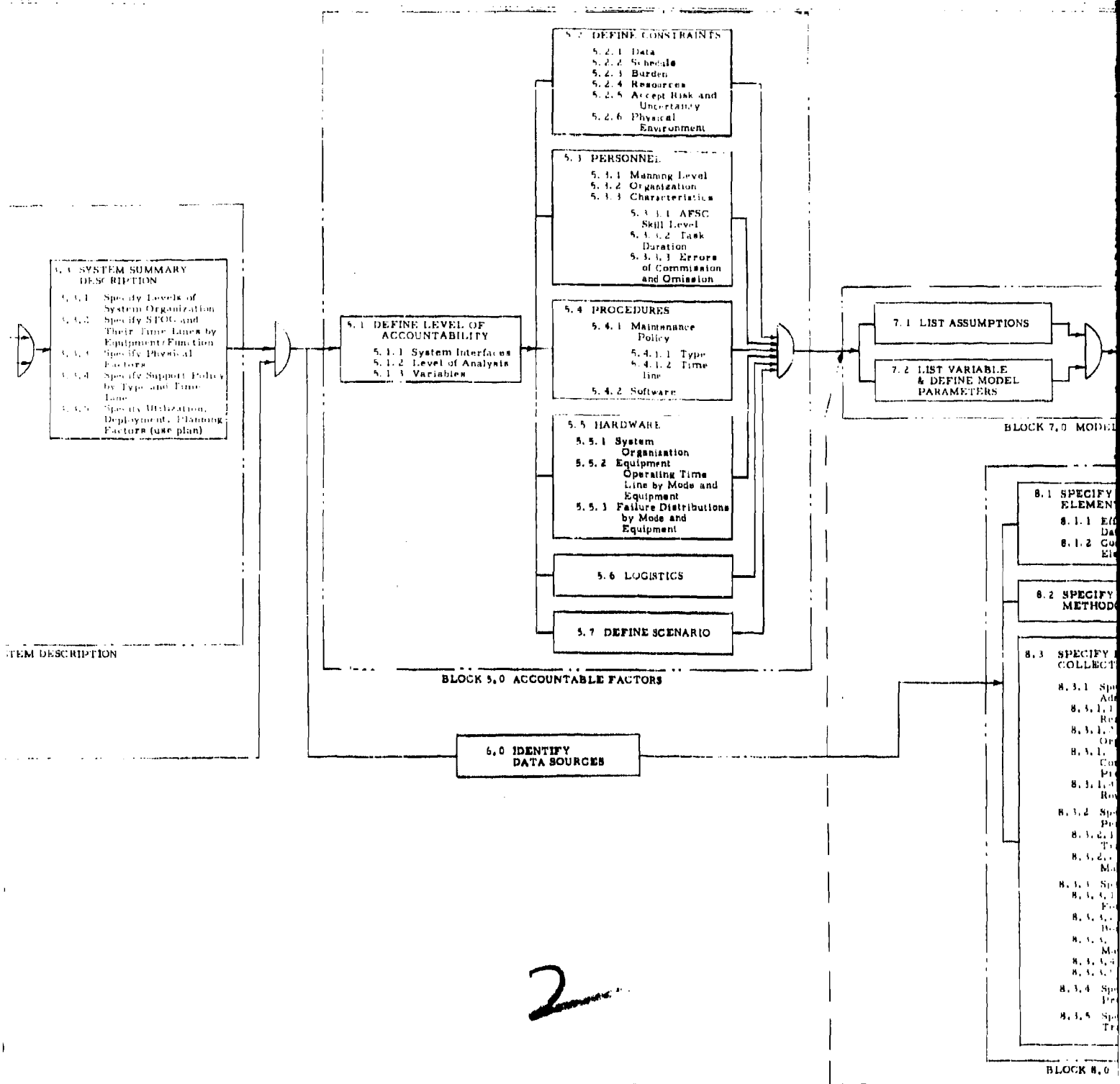
## BLOCK 15.0 CHANGE ANALYSIS

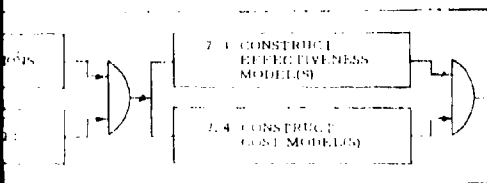
The implementation of a decision based on effectiveness/cost-effectiveness consideration generally implies a change in one or more of the following areas:

- schedule
- model(s)
- system
- requirements.

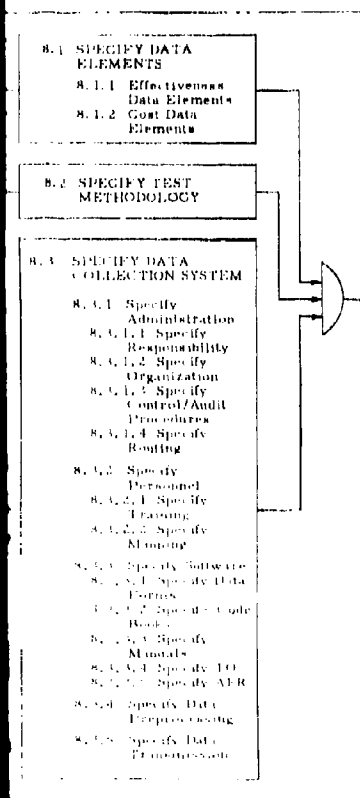
Each iteration of the effectiveness/cost-effectiveness prediction/evaluation/augmentation cycle should be accompanied by a 15.0 Change Analysis against each of these areas. The result of this activity will be a monitoring of the net effect of each decision and the accomplishment of program surveillance.



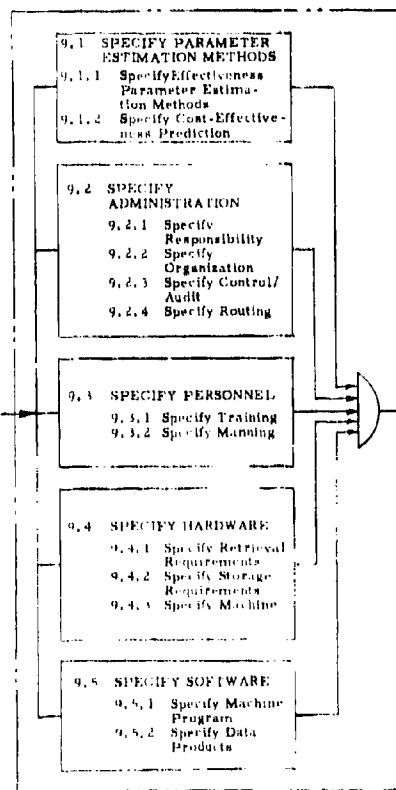




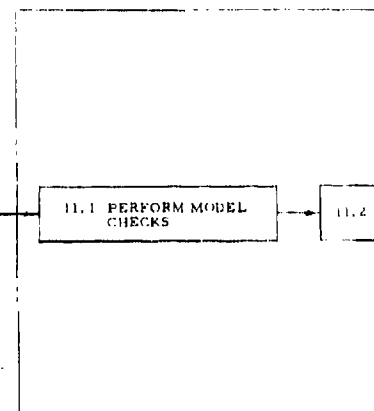
BLOCK 7.0 MODEL CONSTRUCTION



BLOCK 8.0 DATA ACQUISITION



BLOCK 9.0 DATA PROCESSING



10.0 SPECIFY SCHEDULE

3

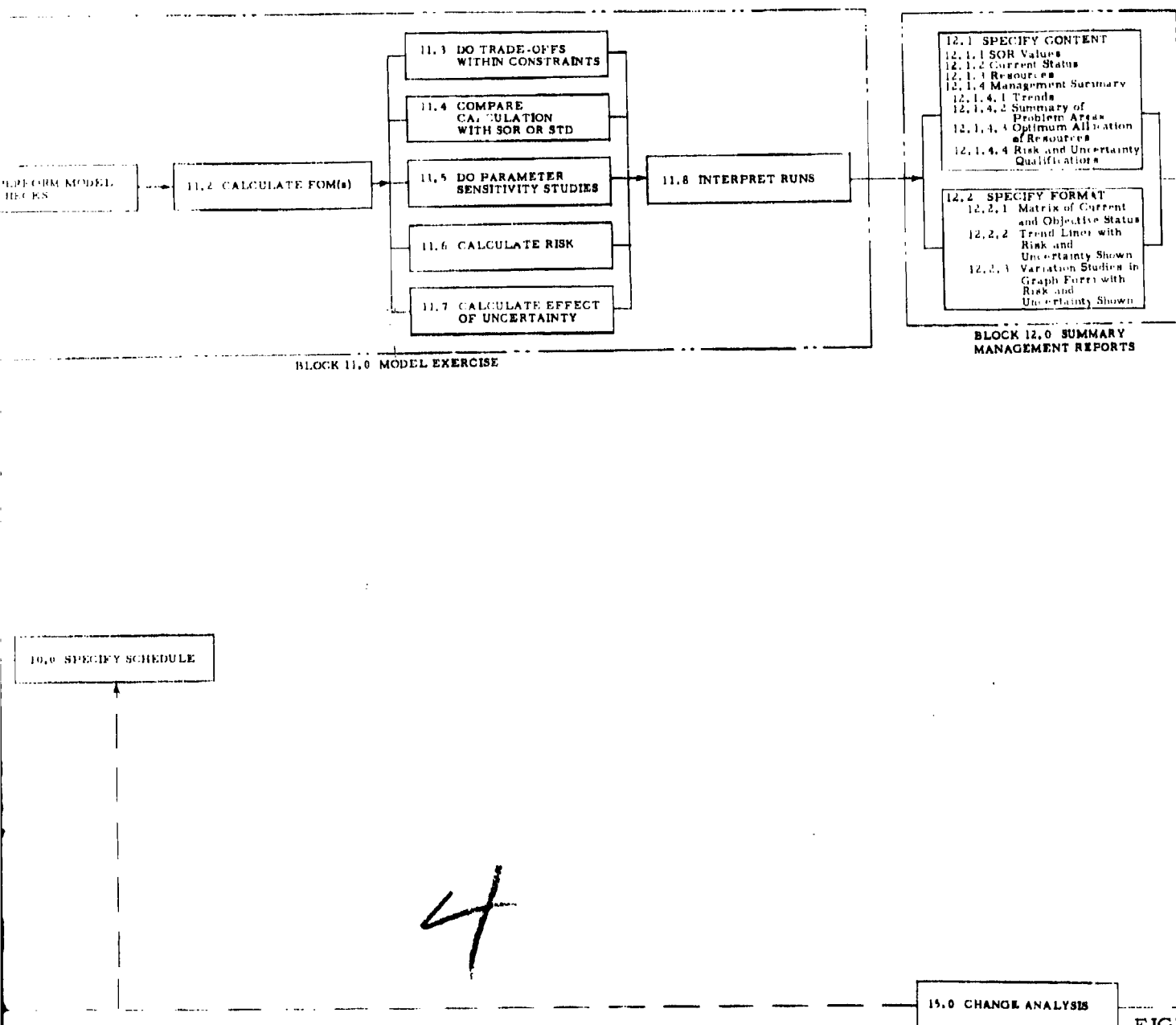


FIGURE 1.

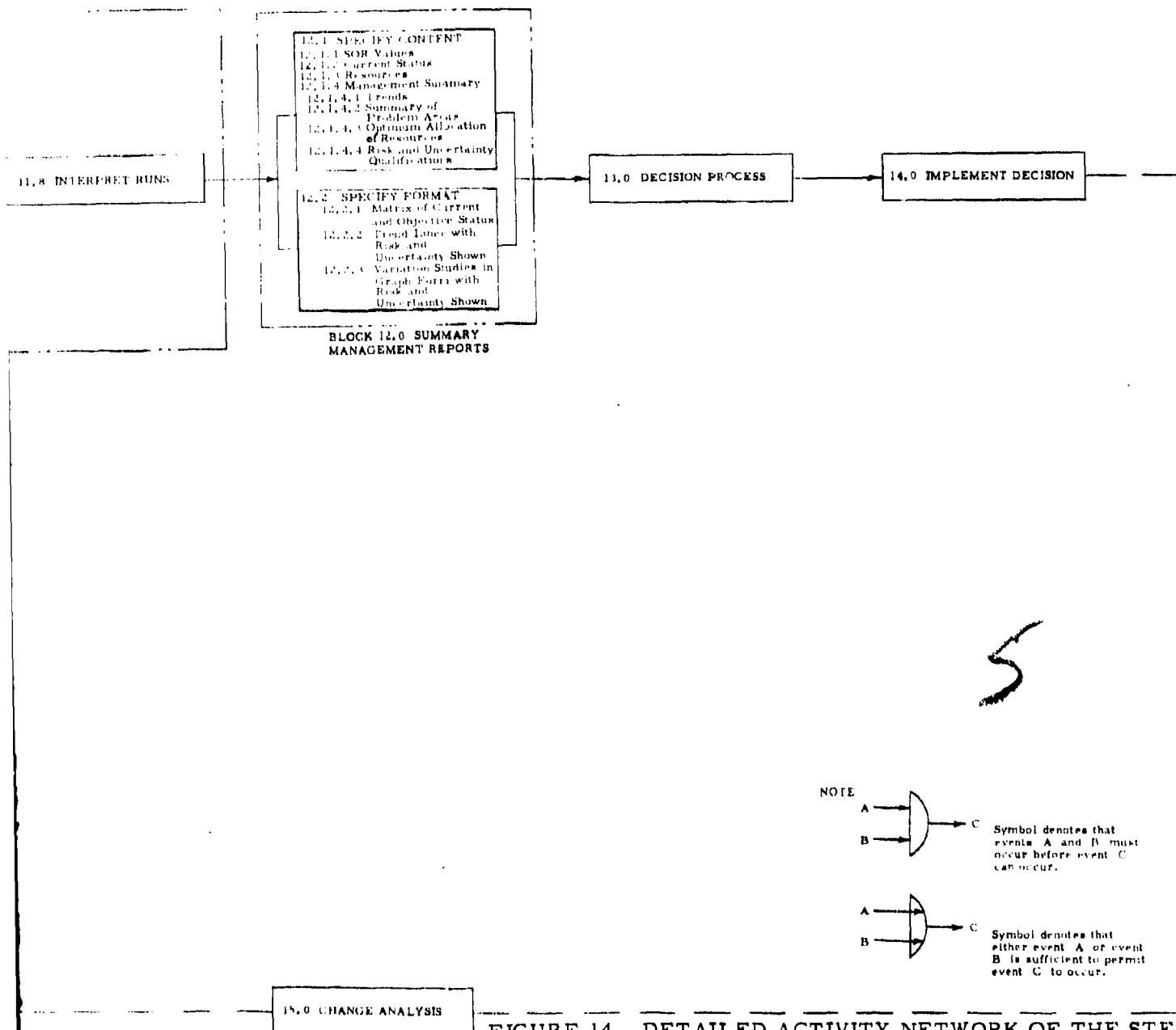


FIGURE 14 - DETAILED ACTIVITY NETWORK OF THE STEPS IN A SYSTEM EFFECTIVENESS/COST-EFFECTIVENESS PREDICTION/EVALUATION/AUGMENTATION CYCLE

APPENDIX II

AN EXAMPLE ANALYSIS  
FOR THE CONCEPTUAL PHASE

## APPENDIX II

### AN EXAMPLE ANALYSIS FOR THE CONCEPTUAL PHASE

#### INTRODUCTION

It is clear from the task outline of Appendix I and from the example analyses<sup>6/</sup> presented by the WSEIAC that the prediction of system effectiveness or cost-effectiveness will generally be an enormously detailed undertaking in the Definition and following phases. On the other hand, during the Conceptual Phase so little information is likely to be available that the analyses will be, at most, skeletonized versions of the later analyses. Because of that very paucity of detail, however, an example of the type of analysis that might be conducted in the Conceptual Phase is a useful means of concurrently illustrating the foregoing task analysis and of emphasizing the principal problem areas which have been unearthed.

To introduce the general concepts of a cost-effectiveness analysis, we shall conduct the analysis in the simplest of terms -- namely, we shall determine how much it costs to achieve a fixed effectiveness for a set of two alternative system configurations. Cost is used to represent the amount of resource expenditure, and effectiveness is a measure of the system's ability to accomplish its mission objectives.

The general approach for making such decisions follows a broad outline which is summarized by the four steps:

- define criteria for selection,
- generate alternatives that satisfy operational requirements and constraints,
- compute resultant values of cost and effectiveness for each alternative, and
- evaluate results with respect to the decision criterion.

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<sup>6/</sup> See Volume III of Task Group II, and Volume III of Task Group IV.

## APPENDIX II

### AN EXAMPLE ANALYSIS FOR THE CONCEPTUAL PHASE

#### INTRODUCTION

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- define criteria for selection,
- generate alternatives that satisfy operational requirements and constraints,
- compute resultant values of cost and effectiveness for each alternative, and
- evaluate results with respect to the decision criterion.

---

<sup>6/</sup> See Volume III of Task Group II, and Volume III of Task Group IV.

Each of these major steps is discussed in some detail here. It is worthwhile, however, to set the stage for such discussions in this introduction.

The criterion for selection must be one that is mission responsive; that is, it must answer the right question. Essentially, the criterion is based on maximizing effectiveness for a given cost or, conversely, minimizing cost for a given level of effectiveness. However, it is also necessary to define the scope of the analysis in terms of resources, system, operational and support constraints. Thus, the fundamental criteria given above naturally evolve into a constrained FOM such as, "maximize effectiveness per dollar, provided effectiveness is greater than  $E^*$  and cost is less than  $C^*$  (where  $E^*$  and  $C^*$  refer to specific limiting values)."

In generating acceptable alternatives, identification of all variable and fixed factors and their costs is required. In addition, the elements of risk and uncertainty as related to these factors and costs and the analysis of effects on other programs must also be considered. Such factors as availability of appropriate data, computational capacity, and restraints in time and effort available for the analysis will play important roles in this phase. A generated alternative is then an acceptable combination of the selected factors with associated risk and uncertainty elements.

Measures of cost and effectiveness for each design alternative must then be computed. The form these measures take is related to the decision criterion. For effectiveness, the measure can range from a simple probability numeric, to an expected value, to the complete distribution of some over-all performance characteristic. The effectiveness model is based on sub-models for reliability, maintainability, and performance. These in turn are based on the variable and fixed factors to be considered such as failure and repair distributions, internal stresses, environment, and design integration.

The cost measure must be one that can treat the major types of resource expenditures on some common basis. Sub-models are required for development costs, operating costs, and support costs both in terms of dollars and schedules. In addition, the burden that a particular alternative places on

other systems and objectives must be evaluated for a complete cost model.

The integration of the separate cost and effectiveness models into a single cost-effectiveness model provides the basis for decisions. It is at this stage that optimization theory becomes applicable, involving such disciplines as mathematical programming, stochastic process theory, calculus of variations, econometrics, and decision theory.

All of the above models must satisfy characteristics related to adequacy, representativeness, consistency, sensitivity, plausibility, criticality, workability, and suitability. In applying the model, it must be emphasized that results of the optimization process can only indicate the best decision within the simplifications, assumptions, restrictions and omissions that were required to circumvent such problems as uncertainties, non-quantifiable factors, and inadequate data, time or computational capacity.

In spite of these potential limitations upon the absolute accuracy of a cost-effective analysis, the framework for a final decision will have been provided. The cost-effectiveness analysis will have reduced the guess work and intuitive estimates of cost and effectiveness, and although the initial results must still be critically evaluated and combined with relevant political and timing factors by the decision maker, there will have been a significant step forward.

The example chosen for illustration is assumed to be a preliminary (first cut) study conducted during the Conceptual Phase in response to a recognized need stated in a ROC or QOR.

It should be carefully noted that this particular example is not intended to serve as a general model of all the required analysis in the Conceptual Phase. The example is presented step by step as a paraphrase of the fifteen principal tasks of the activity network of Figure 14, page 125.

## 1.0 MISSION DEFINITION

1.1 Functional Description A required operational capability (ROC) has been identified in the area of a small, mobile weapons launcher for use at target ranges of 50 to 500 miles against soft targets of small area.

Mobility is required since the anticipated use of the weapon will occur in the forward areas of a moving battle front.

1.2 System Quantitative Requirements The purpose of the preliminary study is to determine whether to:

- (1) proceed with a new SOR,
- (2) respond to the ROC by modifying an existing system, or
- (3) postpone development in favor of additional study and/or exploratory development.

At this stage there are no firm system quantitative requirements. Tentative quantitative requirements will be the desired output of the study if Number 1 is elected.

## 2.0 IDENTIFY RESOURCES

Ordinarily resources would not be specified in a first cut analysis in the Conceptual Phase. Clearly, however, by the end of the Conceptual Phase, a System Program Office must be manned and a program funded. Potential budget and state-of-the-art limitations are factors to be reckoned with.

## 3.0 SYSTEM DESCRIPTION

At this stage of analysis a number of possible system configurations are ordinarily considered, depending upon the ingenuity brought to bear upon satisfying the ROC. The descriptions will, in general, be very gross (tentative) and quite diverse in character. In the following we shall show how two possible candidates among many are compared as part of the weeding out process (exhaustion of alternatives) performed during the Conceptual and early Definition Phases.

3.1 System Number 1 One weapon unit of this proposed system will consist of N launchers, each of which is to contain K missiles.

The concept of this system calls for the assignment of one launcher to a target with up to (N-1) launchers held in reserve. The missile(s) which are stored in the launcher may be assumed to be available (nonfailed) if the launcher is available.

N and K will be specified by the analysis about to be conducted. The launcher is mobile, and it is believed that any of several existing GEM or VTOL vehicles could be modified for use. The proven availability of these vehicles under simulated tactical conditions is known to be,

$$a \geq 0.67$$

The proposed missile would be a short range, solid propellant type similar to several existing missiles whose proven dependability x capability under simulated tactical conditions is known to be,

$$R \geq 0.60$$

One missile of this type is capable of destroying the class of target considered. The definition of effectiveness for this system is:

$E_u^{(1)}$  = the probability of target destruction when an execution directive is received at a random point in time, and one launcher out of N is selected for use.

3.2 System Number 2 There is an existing IRBM which, though it is normally a fixed emplacement missile, could be altered by modifications to become portable by barge.

Therefore, although this system would not be as mobile as system Number 1, its additional range capability would offset the greater mobility of the proposed system.

The IRBM under consideration has a proven effectiveness under simulated tactical conditions of approximately .75 as a fixed emplacement weapon. Its effectiveness as a portable weapon will be somewhat less, but the amount less is expected to be trivial.

The definition of effectiveness ( $E_u$ ) for the IRBM is:

$E_u^{(2)}$  = probability of target destruction when an execution directive is received at a random point in time and one missile is assigned to a target.

#### 4.0 SPECIFY FIGURES OF MERIT

For this first cut analysis the figure of merit assumes the form of a general injunction to "predict the life costs of system Number 1 (which can satisfy the ROC) and compare them to the cost of modifying the existing IRBM system to accomplish the same mission."

Thus, a conservative figure of merit for this preliminary study becomes, "minimize the life cost of a mobile launcher-missile system subject to the constraint  $E_u^{(1)} \geq 0.75$ ."

This figure of merit will permit the life costs of the proposed system to be compared to the costs of support and modification of the existing fixed emplacement IRBM system.

If the costs are significantly different, a clear choice exists. If the costs are similar, further system definition and analysis will be required.

If a clear choice exists, the present analysis would be succeeded by another comparing the "winner" to another contender. This comparison by pairs would continue throughout the Conceptual and Definition Phases until all proposed alternatives have been eliminated.

#### 5.0 SPECIFY ACCOUNTABLE FACTORS

In a first cut analysis of the type being presented here, only the highest level factors are usually accounted for. We shall explicitly include the following in this analysis:

##### System Number 1

- a - availability of an individual launcher
- A - availability of one weapon unit
- $c_f$  - cost of one corrective maintenance action excluding fixed costs
- $C_a$  - estimated cost of the availability "a" of one launcher
- $C_A$  - estimated cost of obtaining a weapon unit availability of "A"
- $C_I$  - total weapon system investment cost
- $C_o$  - fixed costs of weapon maintenance and support

- $C_p$  - estimated cost of obtaining a net weapon unit dependability and capability of "p"
- $C_{P_u}$  - nonrecurring cost of producing one weapon unit having a unit effectiveness  $P_u$
- $C_r$  - total cost of corrective maintenance
- $C_s$  - total weapon system support cost
- $C_R$  - estimated cost of one missile with net dependability and capability "R"
- $C_T$  - total weapon system cost
- $C_u$  - incremental cost of supporting one weapon unit, excluding fixed costs
- $K$  - number of missiles per launcher
- $M$  - number of weapon units required
- $N$  - number of launchers assigned per target
- $p$  - net dependability and capability of one weapon unit, given that at least one launcher is available
- $P_u$  - per unit system effectiveness
- $R$  - product of dependability and capability for a single missile
- $t_d$  - expected downtime of a single launcher for a single corrective maintenance action
- $T$  - total expected useful operational life of system.

#### System Number 2

- $C'_A$  - estimated cost of obtaining a weapon unit availability of "A"
- $C'_I$  - total system investment cost
- $C'_O$  - fixed cost of weapon maintenance and support
- $C'_P$  - estimated cost of obtaining a net weapon unit dependability and capability "p"
- $C'_r$  - expected average yearly cost of corrective maintenance per missile
- $C'_s$  - total system support cost
- $C'_T$  - total cost of one modified IRBM system

- $C'_u$  - incremental cost of supporting one IRBM and its barge, excluding fixed costs
- $M$  - number of required weapon units
- $T$  - total expected useful operational life of system.

It will be noted that the number of parameters differ between systems number 1 and 2. This is to be expected since less detailed estimation is required for the existing IRBM than for the nonexistent GEM launcher.

## 6.0 IDENTIFY DATA SOURCES

(See 8.0 Acquire Data)

## 7.0 MODEL CONSTRUCTION

7.1 Effectiveness Equations for System Number 1 Since the missile(s) which are stored in the launcher may be assumed to be available (nonfailed) if the launcher is available, the availability of a weapon unit ( $A$ ) (for one target) is given by,

$$A = 1 - (1 - a)^N \quad (1)$$

where:

$a$  is the availability of an individual launcher

$(N - 1)$  is the number of launchers held in reserve on the target.

Although a launcher may contain several missiles, any one of the missiles is capable of destroying the class of targets considered. Therefore, if  $R$  is the product of dependability and capability for a single missile if there are  $K$  missiles per launcher, then the net dependability and capability ( $p$ ) of one weapon unit, given that at least one launcher is available is,

$$p = 1 - (1 - R)^K \quad (2)$$

For this study it is desired that  $N$  and  $K$  be selected in an optimum manner (least cost) under the constraint that the unit effectiveness ( $P_u$ ) is such that,

$$P_u = pA \geq E_o \quad (3)$$

where  $E_o$  is the unit effectiveness of the existing fixed emplacement IRBM missile system which could, with some modification be used against the class of targets considered.

$$E_o \cong 0.75 \quad (4)$$

## 7.2 Cost Equations

7.2.1 Aggregate Cost of Weapon System Number 1 The total weapon system cost  $C_T$  is assumed to be adequately expressed by:

$$C_T = C_I + C_s \quad (5a)$$

$C_T$  = total weapon system cost

$C_I$  = total weapon system investment cost

$C_s$  = total weapon system support cost

where

$$C_I = M C_{P_u} \quad (5b)$$

$$C_s = M C_u + C_r + C_o \quad (5c)$$

where

$C_r$  = total cost of corrective maintenance

$M$  = number of weapon units required

$C_{P_u}$  = nonrecurring cost of producing one weapon unit having a per unit effectiveness  $P_u$

$C_u$  = incremental cost of supporting one weapon unit (excluding fixed costs of weapon maintenance/support

$C_o$  = fixed costs of weapon maintenance/support.

### 7.2.2 Cost Estimating Relationship for $C_{P_u}$ for System Number 1

The cost  $C_{P_u}$  for the above system may be expressed as,

$$C_{P_u} = C_A + C_p \quad (6)$$

We shall assume that to a first order approximation,

$$C_A = NC_a \quad (7)$$

$$C_p = KC_R \quad (8)$$

where

$C_A$  = estimated cost of obtaining a weapon unit availability  $A$

$C_p$  = estimated cost of obtaining a weapon unit dependability x capability of  $p$

$C_a$  = estimated cost of obtaining the availability "a" of one launcher

$C_R$  = estimated cost of one missile of dependability x capability of  $R$ .

Substituting Equations (7) and (8) into (1) and (2) respectively, we obtain,

$$C_A = \frac{C_a}{\ln\left(\frac{1}{1-A}\right)} \ln\left(\frac{1}{1-A}\right) \quad (9)$$

$$C_p = \frac{C_R}{\ln\left(\frac{1}{1-R}\right)} \ln\left(\frac{1}{1-p}\right) \quad (10)$$

### 7.2.3 Cost Estimating Relationship for $C_r$ for System Number 1

The expected amount of down time per launcher during an expected operational life time  $T$  is given by,

$$T(1-A)^{1/N}$$

Then the cost of unscheduled maintenance  $C_r$  for  $MN$  launchers is,

$$C_r = c_f \frac{MTN}{t_d} (1-A)^{1/N}$$

where

$c_f$  = cost of one corrective maintenance action, excluding fixed costs

$T$  = expected life of the system

$A$  = availability of a weapon unit (excludes preventive maintenance)

$t_d$  = expected downtime of a single launcher arising from corrective maintenance.

7.3 Cost of a Modified IRBM System (System Number 2) The total cost  $C_T'$  of a modified IRBM system is assumed to be given by,

$$C_T' = C_I' + C_s' \quad (11)$$

$$C_I' = M(C_A' + C_p') \quad (12)$$

$$C_s' = M C_u' + C_o' + C_r' T M \quad (13)$$

where

$C_I'$  = investment cost = cost of modifying IRBM, outfitting barge and procuring IRBM and barge

$C_s'$  = support cost

$C_u'$  = incremental cost of supporting one IRBM and barge (excluding fixed costs)

$C_o'$  = fixed costs of weapon maintenance/support

$C_r'$  = expected average yearly cost of corrective maintenance per missile.

7.4 Statement of the Optimization Problem for System Number 1 It is desired to minimize equation (5a) subject to the constraint (3). We shall do this by means of Lagrangian multipliers.<sup>7/</sup> In the present instance this calls for replacing the constraint (3) with:

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<sup>7/</sup> One of several optimization techniques recommended by the WSEIAC

$$P_u = E_o + S^2 \quad 0 \leq S^2 \leq 1 - E_o \quad (14a)$$

where  $S^2$  is a new variable. However, since (5a) increases monotonically with  $P_u$  we may replace (3) with the simpler constraint

$$P_u \equiv E_o \quad (14b)$$

Given the modified constraint (14b) and the cost equation (5a), the optimization problem may be stated as: Allocate the given unit effectiveness  $P_o$  between A and p in such a way that the sum of the investment cost  $C_I$  and the total life support cost  $C_s$  is a minimum. It should be carefully noted that this optimization implies that development dollars will be balanced against support dollars, a course of action which implies an apportionment between Air Force commands made prior to the Acquisition Phase at a time when the effectiveness of the proposed system is at best a projection based upon historical generic data. Such an apportionment will be subject to a large amount of uncertainty, of which due note will be made later.

7.5 Solution of the Optimization Problem for System Number 1 The solution of the problem as stated above is accomplished as follows: Form a new equation which is the sum of (5a) and the constraint (14)

$$f(\lambda) = C_I + C_s + \lambda(Ap - E_o) \quad (15)$$

Then a necessary condition for an optimum solution to exist is,

$$\begin{aligned} \frac{\partial f}{\partial p} &= 0 \\ \frac{\partial f}{\partial A} &= 0 \\ \frac{\partial f}{\partial \lambda} &= 0 \end{aligned} \quad (16)$$

Hence,

$$\frac{\partial f}{\partial p} = \frac{\partial C_T}{\partial p} + \lambda A = 0 \quad (17a)$$

$$\frac{\partial f}{\partial A} = \frac{\partial C_T}{\partial A} - \lambda p = 0 \quad (17b)$$

$$\frac{\partial f}{\partial \lambda} = pA - E_o = 0 \quad (17c)$$

Combining these equations,

$$\frac{\partial C_T}{\partial A} - \frac{p^2}{E_o} \frac{\partial C_T}{\partial p} = 0 \quad (18)$$

The solution of this equation for  $p$  and Equation (17c) for  $A$  results in a predicted optimum allocation of resources.

Substituting for the derivatives in Equation (18),

$$\begin{aligned} \frac{C_a}{\ln\left(\frac{1}{1-a}\right)} \left(\frac{1}{1-\frac{E_o}{p}}\right) - \frac{c_f T}{t_d \ln(1-a)} \left(\frac{1}{1-\frac{E_o}{p}}\right) \\ - \frac{p^2}{E_o} \frac{C_R}{\ln\left(\frac{1}{1-R}\right)} \left(\frac{1}{1-p}\right) = 0 \end{aligned} \quad (19)$$

which reduces to,

$$p = \frac{E_o - K + \sqrt{(K - E_o)^2 + 4K}}{2} \quad (20)$$

where:

$$K = \frac{E_o \ln(1-R) [C_a t_d + c_f T(1-a)]}{C_R t_d \ln(1-a)} \quad (21)$$

## 8.0 ACQUIRE DATA

Studies which are conducted in the Conceptual Phase have little or no accurate data on the proposed systems. Accordingly, it is necessary to appeal to analogous systems for information. "Analogous" may mean analogous function, or complexity, or both. In the present instance we shall simply assume that available data leads to the parameter estimates

shown in Table VII, where a range of uncertainty has been indicated for  $C_a$ ,  $C_R$ , and  $c_f$ . It is assumed that sufficient historical data exists that the estimates  $a$ ,  $R$ ,  $t_d$ ,  $C_o$ ,  $C_u$ ,  $E_u$ , etc. can be accurately made. It should be carefully noted that these are highly questionable assumptions.

The WSEIAC has identified current data systems as a primary problem area in implementing a system effectiveness or cost-effectiveness program. In particular, it is noted that no adequate historical data sources currently exist. Consequently this example analysis cannot be conducted in general under current circumstances. To alleviate this situation the WSEIAC recommends the creation of a System Effectiveness Information Central (SEIC) which would preserve appropriate historical data. Such data would be obtained from System Information Banks (SIB's) established for each Air Force system at the end of the Conceptual Phase.

#### 9.0 PROCESS DATA

First cut studies of the type being illustrated obviously require no mechanical data processing aids. During the later program phases, however, enormous quantities of data are apt to be generated. Electronic data processing is a necessity.

#### 10.0 SPECIFY SCHEDULE

Schedule enters into Conceptual Phase studies in a very simple way -- it can rule out those alternatives which cannot be delivered in the near future. In the present analysis, for example, an estimation of the expected acquisition times of system 1 and 2 would be made. It is conceivable that the lesser cost-effective system might be acquired on a stop-gap basis if the acquisition time of the alternative system were sufficiently disparate and no other alternative presented itself. Thus, schedule in the Conceptual Phase is a "GO, NO-GO" type of constraint which generally would not appear explicitly in cost-effectiveness equations.

#### 11.0 MODEL EXERCISE

11.1 System Optimization for System Number 1 The optimum choice for  $p$  is found by solving Equation (19) using the estimates of Table VII.

TABLE VII  
PARAMETER ESTIMATES FOR EXAMPLE

| Proposed New System                                     | Modified IRBM                  |
|---------------------------------------------------------|--------------------------------|
| $a \geq 0.67$                                           | $E_u \leq 0.75$                |
| $R \geq 0.60$                                           | $C_A' = 15 \times 10^6$        |
| $t_d = 1 \text{ day}$                                   | $C_p' = 20.4 \times 10^6$      |
| $5.92 \times 10^6 \geq C_a \geq 4.58 \times 10^6$       | $C_u' = 0.15 \times 10^6$      |
| $\$7.1 \times 10^6 \geq C_R \geq \$5.4 \times 10^6$     | $C_o = 3 \times 10^6$          |
| $C_o = \$1.5 \times 10^9$                               | $C_r' = 4.4 \times 10^6$       |
| $C_u = \$0.1 \times 10^6$                               |                                |
| $\$1.096 \times 10^3 \leq c_f \leq \$2.192 \times 10^3$ |                                |
| $T = 10 \text{ years (given)}$                          | $T = 10 \text{ years (given)}$ |
| $M = 100 \quad (\text{given})$                          | $M = 100 \quad (\text{given})$ |

The eight possible optimum solutions for  $p$  indicated by the range of uncertainty of the data of Table VII are shown in Table VIII.

Because of the uncertainty in the data, the optimum choice (see Table VIII) of  $p$ ,  $A$ ,  $N$ ,  $K$ , and costs for 100 weapon units cannot be defined any closer than,

$$0.845 \leq p \leq 0.882$$

$$0.888 \geq A \geq 0.850$$

$$1.97 \geq N \geq 1.71$$

$$2.03 \leq K \leq 2.33$$

$$\$2.007 \times 10^9 \leq C_I \leq \$2.631 \times 10^9$$

$$\$1.744 \times 10^9 \leq C_S \leq \$2.007 \times 10^9$$

$$\$3.762 \times 10^9 \leq C_T \leq \$4.619 \times 10^9$$

11.2 Cost of System Number 2 From Equations (11), (12) and (13), and Table VII we obtain for 100 targets,

$$C_I' = \$3.54 \times 10^9$$

$$C_S' = \$4.418 \times 10^9$$

$$C_T' = \$7.958 \times 10^9$$

11.3 Costs as a Function of Number of Targets  $M$  Although the number of targets  $M$  has been specified, this requirement is also subject to uncertainty. The relative costs of system number 1 and 2 as a function of the number of targets is shown in Figure 15.

11.4 Interpretation of Results In spite of the uncertainty in the data for system number 1, this system should cost about one half the amount of system number 2 for coverage of 100 targets. However, it should be noted from Figure 15 that both systems are equally cost-effective for about 30 targets, and that system number 2 is most cost-effective below 27 targets.

TABLE VIII  
OPTIMUM CHOICE OF P, A, N, K, AND COSTS FOR 100 WEAPON UNITS

| $C_a$<br>( $\times 10^{-6}$ ) | $C_R$<br>( $\times 10^{-6}$ ) | $c_f$<br>( $\times 10^{-3}$ ) | P    | A    | N    | K    | $C_I$<br>( $\times 10^{-9}$ ) | $C_s$<br>( $\times 10^{-9}$ ) | $C_T$<br>( $\times 10^{-9}$ ) | System<br>No. 1 |
|-------------------------------|-------------------------------|-------------------------------|------|------|------|------|-------------------------------|-------------------------------|-------------------------------|-----------------|
| 5.92                          | 7.1                           | 2.192                         | .866 | .866 | 1.81 | 2.19 | 2.631                         | 1.988                         | 4.619                         | System<br>No. 1 |
|                               | 5.4                           | 2.192                         | .882 | .850 | 1.71 | 2.33 | 2.272                         | 1.962                         | 4.234                         |                 |
|                               | 7.1                           | 1.096                         | .856 | .876 | 1.88 | 2.11 | 2.617                         | 1.758                         | 4.375                         |                 |
|                               | 5.4                           | 1.096                         | .872 | .860 | 1.77 | 2.24 | 2.261                         | 1.744                         | 4.005                         |                 |
| 4.58                          | 7.1                           | 2.192                         | .856 | .875 | 1.88 | 2.11 | 2.364                         | 2.007                         | 4.371                         |                 |
|                               | 5.4                           | 2.192                         | .872 | .860 | 1.77 | 2.24 | 2.023                         | 1.978                         | 4.001                         |                 |
|                               | 7.1                           | 1.096                         | .845 | .888 | 1.97 | 2.03 | 2.349                         | 1.771                         | 4.120                         |                 |
|                               | 5.4                           | 1.096                         | .860 | .872 | 1.85 | 2.15 | 2.007                         | 1.755                         | 3.762                         |                 |
|                               |                               |                               |      |      |      |      | 3.54                          | 4.418                         | 7.958                         | System<br>No. 2 |

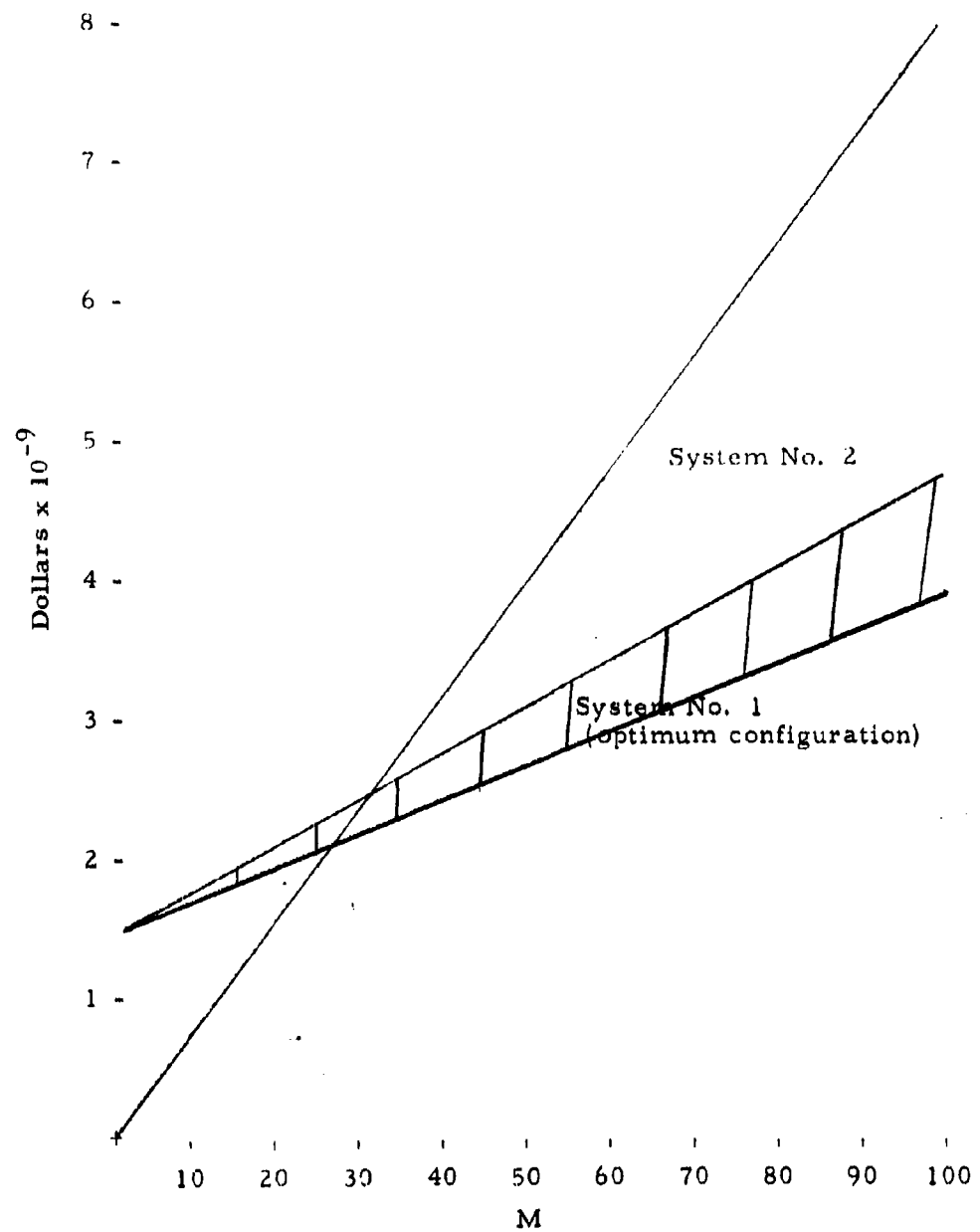


FIGURE 15  
RELATIVE (MINIMAL) COSTS OF SYSTEM NUMBER 1 AND 2  
AS A FUNCTION OF THE NUMBER OF TARGETS

## BLOCK 12.0 MANAGEMENT SUMMARY REPORTS

The purpose of a management summary report is to apprise the decision maker of all facts and conjectures relevant to the potential solution of a problem.

In the present example, the problem is to satisfy the ROC or QOR by either selecting between potential system configurations or by entering exploratory development. Thus, the content of a summary report of the present example analysis would contain at least as much as has been presented here for three reasons:

- a well informed management is more apt to make decisions that withstand the cold clarity of hindsight
- a review of previous analyses becomes necessary if the uncertainty aspects of a ROC or QOR change
- the Conceptual Phase studies should be available for guidance during later phases if it is elected to proceed with a TSOR.

The recommended content of a documentation of a Conceptual Phase study is that used in this example; namely, a paraphrase of the first eleven steps of the activity network of Figure 14.

### BLOCK 13.0 THE DECISION PROCESS

The rational process of cost-effectiveness selection between competing alternatives must eventually terminate with the exhaustion of alternatives. In many real situations the proper decision will not be as clear cut as we have (conveniently!) chosen to illustrate it. All the available facts, including the estimates of uncertainty, have been evaluated, and we choose system number 1. Notice that even here, however, we have had to exercise that indispensable prerogative of management - judgment.<sup>8/</sup>

Before we pat ourselves on the back, however, let us pursue this decision business a bit further. Now that the bathing beauty contest is over, let's examine the measurements of the winner. Specifically, what set of quantitative requirements do we put in the TSOR? The achievable value  $E_u = .75$  which was the basis of our comparative analysis? Something less? Something better? How do we decide what probability values are minimum acceptable?

#### How much is good enough?

WSEIAC does not tell us. They identify this as a problem area and recommend that the problem be studied.

How serious a problem is it? Can it be ignored? We may judge from the following WSEIAC observation.

The minimum acceptable quantitative requirements of a certain recent SOR are given piecemeal in terms of separate probabilities and performance limits without obvious relation one to another. When combined in an over-all system effectiveness number (along WSEIAC lines) these requirements suggest that if this system works less than 4 times out of 100, it is acceptable! Would you cross a street if those were your odds in traffic?

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<sup>8/</sup> In our judgment there will never be less than 32 targets.

#### 14.0 IMPLEMENT DECISION

In view of the comments under 13.0 The Decision Process, and assuming that all candidate systems have been evaluated, the next course of action is as follows:

- establish a TSOR for a mobile missile launcher of the GEM type with a unit effectiveness  $E_u \geq 0.75$ . (The intent is to firm up  $E_u$  during the Definition Phase.)
- establish an SIB for the new system
- document the Conceptual Phase studies and include them in the TSOR by reference
- budget resources
- establish a schedule for initial operational capability.

#### 15.0 CHANGE ANALYSIS

(not pertinent)

APPENDIX III

GLOSSARY OF SYSTEM EFFECTIVENESS  
AND COST-EFFECTIVENESS TERMS

### APPENDIX III

#### GLOSSARY OF SYSTEM EFFECTIVENESS AND COST-EFFECTIVENESS TERMS

This glossary of terms contains definitions of those words which are commonly used in the WSEIAC Task Group reports, but which may be unfamiliar to the reader or not of standardized usage. Those words whose meaning is evident from the context or which have come into standard usage among the various technical disciplines are not defined here.

Accountable factors Those physical and organizational facts pertaining to an item and its operational environment which are specifically considered in the construction of a model. For example; failure rate, repair time, manning, maintenance policy, boundary conditions and constraints.

Acquisition Phase The third of the four phases of a system life-cycle. It starts after issuance of the System Program Directive and ends with acceptance by the user of the last operating unit in a certain series, or until the Specific Operational Requirement has been demonstrated through Category II testing and all required updating changes resulting from the testing have been identified, approved, and placed on procurement, whichever occurs later. It subsumes system development and production.

Alert That portion of uptime when an item is in a vigilant state and is thought to be non-failed and/or is waiting the execution directive to perform its intended mission.

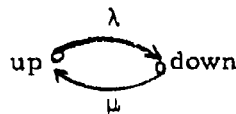
Apportionment To divide and assign an index or portion of the whole among its constituent parts or elements.

Availability A measure of the system condition at the start of the mission, when the mission is called for at an unknown (random) point in time.

- True pointwise availability - The probability that a system is, in fact, usable at a specific point in time. (It should be carefully noted that for a system to be truly available, it must not only be thought to be usable but must, in fact, be in a usable condition).
- Apparent pointwise availability - The probability that a system is apparently usable, but may, in fact, be non-usable.
- Interval availability - Either true or apparent, is the average of true or apparent pointwise availability, respectively, over a specified interval of time  $T$ .
- Steady state availability - The limiting value of interval availability as the time interval  $T$  increases without bound.

Mathematically, these definitions are expressed as follows:

For the simple case where a system is down when failed, and up when non-failed (e.g., no preventive maintenance or other type interruptions), and  $\lambda$  is failure rate,  $\mu$  is repair rate (exponential repair and failure distributions):



Let  $P_u(t)$  = pointwise availability.

Then  $P_d(t) = 1 - P_u(t)$  = probability of being in repair.

Now if

$P_u(0)$  = probability of being up at time zero, and

$P_d(0)$  = probability of being down at time zero where

$P_{u/u}(t)$  = the conditional probability of being up at time  $t$ ;  
given you are initially up, and

$P_{u/d}(t)$  = the conditional probability of being up at time  $t$ ;  
given you are initially down, then

$$P_u(t) = P_u(0) P_{u/u}(t) + P_d(0) + P_{u/d}(t).$$

Thus it can be shown that

$$P_{u/d}(t) = \frac{\mu}{\mu + \lambda} - \frac{\mu}{\mu + \lambda} e^{-(\lambda + \mu)t}$$

$$P_{u/u}(t) = \frac{\mu}{\mu + \lambda} + \frac{\lambda}{\mu + \lambda} e^{-(\mu + \lambda)t}.$$

Interval availability  $A_I$  is then,

$$A_I = \frac{1}{T} \int_0^T P_u(t) dt$$

and steady state availability  $A[\infty]$  is given by,

$$A[\infty] = \lim_{T \rightarrow \infty} A_I = \lim_{t \rightarrow \infty} P_u(t)$$

if  $\lim P_u(t)$  exists. The limit will usually exist unless strictly periodic preventive maintenance occurs on the system.. In this case, however,  $A_I$  still will exist and therefore  $A[\infty]$  exists.

An estimate  $\hat{A}[\infty]$  of  $A[\infty]$  may be obtained from the following relationship:

$$\hat{A}[\infty] = \frac{MTBSI}{TCT}$$

MTBSI = mean time between system interruptions

TCT = total calendar time of observation.

Calendar time The total number of calendar days or hours in a designated period of observation.

Capability A measure of the ability of a system to achieve the mission objectives, given the system condition(s) during the mission. It specifically accounts for the performance spectrum of a system.

Conceptual Phase The first of the four phases of a system life-cycle. It is initiated by a statement of a general need for a particular operational capability in an ROC or QOR. The phase extends from determination of a broad objective or need, to Air Force approval of the Program Change Proposal covering the second phase of the system life-cycle.

Constraint A bound or restraint on a parameter, variable, factor, function or operation.

Corrective maintenance That maintenance performed to restore an item to a satisfactory condition by providing correction of a malfunction.

Corrective maintenance time The time that begins with the observation of a malfunction of an item and ends when the item is restored to a satisfactory condition. It may be subdivided into 'active maintenance time' and 'delay time' and does not necessarily imply equipment or system downtime if alternate modes of operation or redundancy are used.

Cost-effectiveness A term used to relate estimated or assessed cost to

estimated or assessed effectiveness. It is the value received (effectiveness) for the resources consumed or applied (cost).

Cost estimating relationship (CER) A functional expression that relates cost to a variable or set of variables; e.g., cost per pound of jet engine thrust.

Cost optimization The process of seeking a minimum cost program wherein effectiveness is ordinarily an unconstrained variable.

Data element (basic) A discrete measurement or item usually used as a block entry on a reporting form.

Data element (computational) A computed output utilizing two or more basic data elements.

Definition Phase The second of the four phases of a system life-cycle. It is initiated by a System Definition Directive and ends with issuance of a System Program Directive. The purpose of this phase is to refine a grossly defined system down to the subsystem level.

Dependability A measure of the system condition at one or more points during the mission; given the system condition(s) at the start of the mission. It may be stated as the probability (or probabilities or other suitable mission oriented measure) that the system (1) will enter and/or occupy any one of its significant states during a specified mission and, (2) will perform the functions associated with those states.

Downtime That portion of calendar time during which the item is not in condition to perform its intended function.

Environment The aggregate of all conditions and influences which affect the operation of an item; e.g., physical location, temperature, humidity, pressure, shock, etc.

Failure The inability of an item to perform its intended function. (The intended function must be specified. All failures are assumed to have an assignable cause.)

Failure, dependent (secondary) A failure caused by the malfunctioning of associated item(s).

Failure, independent (primary) A failure which is unrelated to the malfunctioning of associated item(s).

Failure, Mean Time<sup>8/</sup> Between (MTBF) The average (mean) time between failures of repairable items calculated from the total operating time and the total population.

Failure, random A failure which is random with respect to its time (or cycles, etc.) of occurrence. It is also used to denote failures that arise from an exponential failure distribution.

Failure rate The number of failures of an item expressed as a relationship to a measure of life. The failure rate of a probability distribution of units-to-failure is mathematically defined as the (conditional) probability density function of units-to-failure, given that the device has not failed prior to a given unit "u." For example, if  $f(t)$  is the (absolute) probability density function of times-to-failure, and  $dt$  is some small interval of time starting at  $t$ , the  $f(t) dt$  represents the proportion of a population of devices starting at time  $t$  which fail in the time interval  $(t, t + dt)$ . If  $F(t)$  is the cumulative distribution of times-to-failure, then the failure rate lambda ( $\lambda$ ) is expressed as  $\lambda = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{R(t)}$ .

In the case of exponentially distributed times-to-failure, the failure rate  $\lambda$  equals  $1/m$ , where  $m$  is the mean time between failures. The failure rate  $\lambda$  in any period of time can be computed by taking the ratio of the failures  $f$  during the operating period to the number of equipments  $N$  at the start of the operating, that is  $\lambda(t) = f/N$ . This figure of merit is sometimes referred to as the failure hazard, instantaneous failure rate, hazard rate or hazard function. For a mathematical treatment refer to Lloyd, David and Lipow, Myron, Reliability: Management, Methods, and Mathematics, Space Technology Series; Prentice Hall, 1962, p. 130, ff.

Failures (wearout) Those failures which occur as a result of deterioration processes or mechanical wear and whose rate of occurrence increases

<sup>8/</sup> The definition holds for time, cycles, miles, events and other units of life measurement.

with time. Wearout failures are those failures that occur generally near the end of life of an item and are usually characterized by chemical or mechanical changes. These are failures which could have been prevented by a replacement policy based on the known wearout characteristics. A specific example would be motor brush wearout.

Figure of Merit (FOM) A statement, either verbal or analytic, which relates mission objectives to quantitative system requirements. It is a statement of the ability of a system to meet an operational need which includes the recognition of risk and uncertainty. A specified value of system effectiveness is an FOM. The injunction to minimize program costs subject to a specified constraint on program objectives is also an FOM.

Human factors Human psychological characteristics relative to complex systems, and the development and application of principles and procedures for accomplishing optimum man-machine integration and utilization. The term is used in a broad sense to cover all biomedical and psychosocial considerations pertaining to man in the system.

Lethality The probability that weapon effects will damage the military objective to a specified degree.

Maintainability Maintainability is a characteristic of design and installation which is expressed as the probability that an item will conform to specified conditions within a given period of time when maintenance action is performed in accordance with prescribed procedures and resources. It is denoted by the symbol M.

Mean-time-between-failure (MTBF) The statistical mean of the distribution of time between successive failures excluding downtime. The summation of time between failures excluding downtime during a given time period divided by the total number of failures during the same interval is an estimate of the MTBF. (See 'failure')

Mean-time-between-system-interruptions (MTBSI) The statistical mean of the distribution of the time between system interruptions. The total uptime in a given time period divided by the total number of system interruptions

in the same time period is an estimate of MTBSI.

Mean-time-to-repair (MTTR) The statistical mean of the distribution of corrective maintenance time. The summation of the durations of corrective maintenance time during a given time period divided by the total number of repair actions during the same time period is an estimate of MTTR.

Mission duration The period of time in which an item is performing a specified mission.

Mission profile A sequential and chronological description of the mission of an item.

Model Any device, technique, or process by means of which the specific relationships of a set of quantifiable system parameters may be investigated.

Operational factors Various factors, generated by the operational concept, which affect the mission accomplishment. Among these factors are the number of vehicles, the availability requirements, and training requirements.

Operational Phase The period in the system life-cycle which starts with the delivery of the first inventory unit or installation to the using command and terminates with disposition of the system from the inventory.

Operational profile (See 'mission profile')

Optimization The process of searching for the most favorable combination of two or more independent and conflicting variables.

Parameter A quantity employed in an analysis as a symbolic representation of a system attribute.

Penetrability The probability that a weapon system will survive a defense environment and arrive at the military objective intact. (See survivability)

Preventive maintenance That maintenance performed to retain an item in satisfactory operational condition by providing systematic inspection, detection and prevention of incipient failure such as maintenance to perform measurements; care of mechanical wearout items; front panel adjustment, calibration and alignment; cleaning; etc.

Reaction time The time required to initiate a mission, measured from the time the execution directive is received.

Ready time The period of time during a mission that the item is available for operation, but is not required. (Different from 'alert' time)

Redundancy The existence of more than one means for an item to perform a function, where all means must fail before there is an over-all failure of the item.

Redundancy, parallel That redundancy in which a function is performed by simultaneous operation of two or more items, anyone of which is capable of performing the function alone in the event of failure of one or more of the other items.

Redundancy, standby That type redundancy in which an alternate means of performing the task is available and is either switched on by a malfunction sensing device when the primary item fails, for example, or turned on after failure of the primary item.

Reliability (R) The probability that an item will perform a required function, under specified conditions, without failure, for a specified period of time.

Reliability, achieved A statistical estimate of reliability based on actual demonstration under specified conditions. The specified conditions may be test conditions or operational conditions, but the conditions must be clearly stated. (See 'inherent reliability' and 'operational reliability')

Reliability, inherent The theoretical maximum reliability of a design assuming no design changes, and operation in an ideal, standard or theoretical environment; for example, a standard summer day.

Reliability, minimum acceptable A reliability below which the item is considered unacceptable; also, a contractual requirement used as a condition for acceptance. Conditions of calculation and measurement must be clearly stated.

Reliability, operational The reliability of an item when operating and being maintained in a specified operational environment, usually by military personnel. (See 'inherent reliability.')

Repair The corrective maintenance process of returning an item to a specified condition by either repairing in place; removing, repairing and replacing the same item; or by replacing with a like serviceable item.

Resources Resources are men, money, materiel, facilities, time, documentation and intangibles such as morale, skills and technology. Materiel is supplies, spares, consumables, equipment, raw materials, tools and the like. Documentation is documented procedures, policy, engineering drawings, methods, techniques and historical information on events and actions. Such activities as training are a resource, but they are not considered resources in the strictest sense. Training enhances the value of resources; e.g., increases the ability of men to perform, or increases the effectiveness or efficiency or value of documentation (procedures, policy, etc.), but is not itself a resource.

Risk The calculable odds associated with either a system significant event or achievement of program objectives.

Skill levels The classification system used to rate Air Force personnel as to their relative abilities to perform their assigned jobs.

Specific Operational Requirement (SOR) An Air Force document containing the definition of the qualitative and quantitative system requirements.

State An identifiable and unique condition of a system or subsystem.

Subsystem A composite of equipment, skills, and techniques which performs a unique function (e.g., navigation), but which is not self-sufficient to perform the complete operational role.

Support cost The cost in dollars or some other suitable measure, of those resources expended in the maintenance of an item. Note that all resources (see 'resources') are not necessarily expendable (e.g., morale, documentation) or may not be expendable for a particular situation except for depreciation or obsolescence (e.g., facilities, equipment).

Support cost, indirect Those expended resources, while not expended directly in support of the maintenance operation, contribute to the over-all maintenance mission by supporting overhead operations, administration, facility records and statistics, supervision, facilities upkeep, etc.

Survivability The probability that a system will survive in an attack environment. The distinction between penetrability and survivability (see 'penetrability') is a matter of degree only.

System A composite of equipment, skills and techniques capable of performing and/or supporting an operational role. A complete system includes related facilities, equipment, material, services and personnel required for its operation to the degree that it can be considered a self-sufficient unit in its intended operational and/or support environment.

System effectiveness A measure of the extent to which a system may be expected to achieve a set of specific mission requirements expressed as a function of availability, dependability and capability.

System interruption Any event which removes the system from an immediately usable condition. Failures (known or unknown), planned or unplanned maintenance, and a variety of administrative actions such as crew-training exercises, are all potential causes of system interruption.

System life-cycle A system is considered to evolve through four relatively distinct phases:

- conceptual (feasibility)
- program definition
- acquisition
- operational.

System significant event Any change of system state which effects cost or effectiveness.

Task Analysis An analytical process employed to determine the specific behaviors required of human components in a man-machine system. It involves determining, on a time base, the detailed performance required of a man and machine, the nature and extent of their interactions, and the

effects of environmental conditions and malfunctions. Within each task, behavioral steps are isolated in terms of perceptions, decisions, memory storage, and motor outputs required, as well as the errors which may be expected. The data are used to establish equipment design criteria, personnel, training requirements, etc.

Uncertainty A condition, event, outcome, or circumstance the extent, value, or consequence of which is not predictable.

Uptime That portion of time that an item is available to perform as intended.

Variable Those parameters or quantities of an analysis the use of which, when varied, will result in variations in resources, system effectiveness, or the cost of accomplishing program objectives.

APPENDIX IV

ABSTRACTS AND SUMMARIES  
OF  
WSEIAC REPORTS BY TASK GROUP

**APPENDIX IV**  
**ABSTRACTS AND SUMMARIES**  
**OF**  
**WSEIAC REPORTS BY TASK GROUP**

This section includes abstracts as they appear in each of the ten (10) volumes which comprise the final reports of the five task groups. In addition to the abstracts, brief summaries of the contents of the reports are presented. This will allow the reader to obtain a grasp of the scope and effort represented by the entire study, which obviously cannot be presented in detail in this integrated summary report.

## A. TASK GROUP I, "REQUIREMENTS METHODOLOGY"<sup>(1)</sup>

### 1. Abstract

The objective of Task Group I was "To review present procedures being used to establish system effectiveness requirements and recommend a method for arriving at requirements that are mission responsive." Applicable documents were examined, including Department of Defense Directives and Instructions, Air Force Regulations, Manuals, Specifications, Office Instructions, etc., that might be used to establish effectiveness requirements. Detailed examination of the Specific Operational Requirement (SOR) and the companion Directorate Office Instruction (DOI) 11-7 resulted in the preparation of a proposed Air Force Manual (Appendix I). This document provides checklists, guidelines, and procedures for SOR preparation that include the significant elements of system effectiveness. A proposed Air Force Regulation (Appendix II) was developed to formalize a program of effectiveness evaluation and prediction for the system life-cycle. Policy, concepts, and major command responsibilities are developed. Additional conclusions and recommendations are submitted relative to effectiveness requirements that constitute necessary steps to development of an Air Force wide system effectiveness management program.

### 2. Summary

The attention of Task Group I was first directed at delineating the scope of this rather generally stated problem. Use of the term "requirements" was interpreted as having reference to those formal published Air Force documents which are prepared during the Conceptual Phase of system life and which provide basic guidance for the more detailed management documents prepared during the Definition and Acquisition Phases. However, not all of the Conceptual Phase was included in the scope of the Task Group I area of interest. As officially defined, the Conceptual Phase of development includes the establishment of a System Program Office (SPO), the preparation of a Preliminary Technical Development Plan (PTDP) and a Program Change Proposal (PCP), terminating when the program is approved by the

Office of the Secretary of Defense (OSD). Task Group I activity is directed at only certain parts of the first portion of this Conceptual Phase. Feasibility studies which are often the forerunner of new systems, are not regarded as being a subject of interest. Advanced Development Objectives (ADO's) are also excluded from consideration because they are by definition directed at the experimental, not the operational inventory.

The documents which remain include Qualitative Operational Requirements (QOR's), Operational Support Requirements (OSR's), and Specific Operational Requirements (SOR's). The QOR is a statement of need, expressed by a command, and is used as a basis for preparation of an SOR or OSR. Both of these latter documents are sufficiently similar to permit the same general considerations of methodology and content to be applied to both. The scope of the study is therefore limited to the preparation of SOR's, with the understanding that recommendations can be extrapolated to OSR's where appropriate.

a. Proposed Air Force Manual Task Group I reviewed the procedures proposed in the draft version of DOI 11-7, AFDORQ, Administrative Practices, Specific Operational Requirement. This instruction did not incorporate effectiveness requirements; consequently, a rewrite of the instruction was instituted. In the course of this rewrite, it was apparent that a systematic approach must be provided to enable all SOR writers to follow a standard procedure. A checklist was developed which embodied all of the provisions of DOI 11-7 and added the concept of weapon system effectiveness. A natural outgrowth of the checklist was a set of instructions for its use, and the two together have evolved into a proposed Air Force Manual for developing SOR's. The proposed manual is included as Appendix I to this report and is a principal output of the task group. The manual is patterned after the present Department of the Air Force, Headquarters United States Air Force, Directorate of Operational Requirements, Departmental Operating Instruction (DOI 11-7). The proposed manual subsumes all of the administrative practices contained in DOI 11-7 and provides:

- (1) a comprehensive checklist for writing an SOR which covers the significant elements of system

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- (1) a comprehensive checklist for writing an SOR which covers the significant elements of system

performance and system effectiveness;

- (2) a format for SOR's defined so that the sections and the main paragraphs of every section bear the same number, title, and contents;
- (3) a basis for quantitative requirements to be entered for all system performance and system effectiveness elements.

b. Proposed Air Force Regulation The introduction of the concept of effectiveness in an SOR must be supported by a program for evaluation and prediction during the life of the system. Accordingly, Task Group I has prepared a proposed regulation (Appendix II) which calls for such a program and assigns command responsibilities. During the preparation of this proposed regulation, meetings were held with representatives from Task Group II in order that the concepts and definitions used by that Task Group would be reflected in the draft. It should be noted that this regulation calls for both an evaluation program and an assurance program prior to evaluation. In addition, it provides for experience retention (and information dissemination) through establishment of a System Information Bank (SIB) for each new system, and a System Effectiveness Information Central (SEIC) which will be responsible for final storage and retrieval of all system effectiveness information.

B. TASK GROUP II, "PREDICTION - MEASUREMENT"

VOLUME I  
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS<sup>(2)</sup>

1. Abstract

Concepts of system effectiveness measurement and prediction, presented in detail in Volume II, are summarized briefly in this volume. Eight formalized tasks necessary to evaluate effectiveness are reviewed. Summaries of four illustrative examples, presented in detail in Volume III, are given. These examples provide useful guidelines for effectiveness evaluation at various phases of system life-cycle. Conclusions concerning the present state of system effectiveness evaluation are presented. A series of recommendations are proposed for Air Force adoption.

VOLUME II  
CONCEPTS, TASK ANALYSIS, PRINCIPLES  
OF MODEL CONSTRUCTION<sup>(3)</sup>

1. Abstract

Concepts of system effectiveness including the three principal terms, availability, dependability, and capability, are presented. Eight specific tasks required to evaluate effectiveness during any phase of system life are presented. A mathematical structure appropriate to effectiveness model construction is described. Using the above task analysis and the model framework, a hypothetical example is presented. Results of the evaluation illustrate effectiveness analysis methods and possible alternate decisions available. Application of simulation methods to the example are discussed. The appendixes contain summaries of four typical examples of the application of effectiveness evaluation methods to various Air Force systems (presented in detail in Volume III). An airborne avionics system, an intercontinental ballistic missile system, a long range radar surveillance system, and a spacecraft system are described.

2. Concept of Effectiveness

System effectiveness concepts adopted by Task Group II are summarized below:

System Effectiveness is a measure of the extent to which a system may be expected to achieve a set of specific mission requirements and is a function of availability, dependability and capability.

Availability is a measure of the system condition at the start of a mission and is a function of the relationships among hardware, personnel and procedures.

Dependability is a measure of the system condition at one or more points during the mission; given the system condition(s) at the start of the mission and may be stated as the probability (or probabilities or other suitable mission oriented measure) that the system (1) will enter and/or occupy any one of its significant states during a specified mission and, (2) will perform the functions associated with those states.

Capability is a measure of the ability of a system to achieve the mission objectives; given the system condition(s) during the mission, and specifically accounts for the performance spectrum of a system.

The objectives of system effectiveness evaluation are to:

- (1) evaluate system designs and compare alternative configurations
- (2) provide numerical estimates for use in defense planning
- (3) provide management visibility at every phase of a system's life cycle of the extent to which the system is expected to meet its operational requirements (SOR).
- (4) provide timely indication of the necessity for corrective actions
- (5) compare the effect of alternative corrective actions.

### 3. Principal Tasks

Eight formalized tasks essential to evaluation of system effectiveness were identified by Task Group II. These are presented in the accompanying diagram.

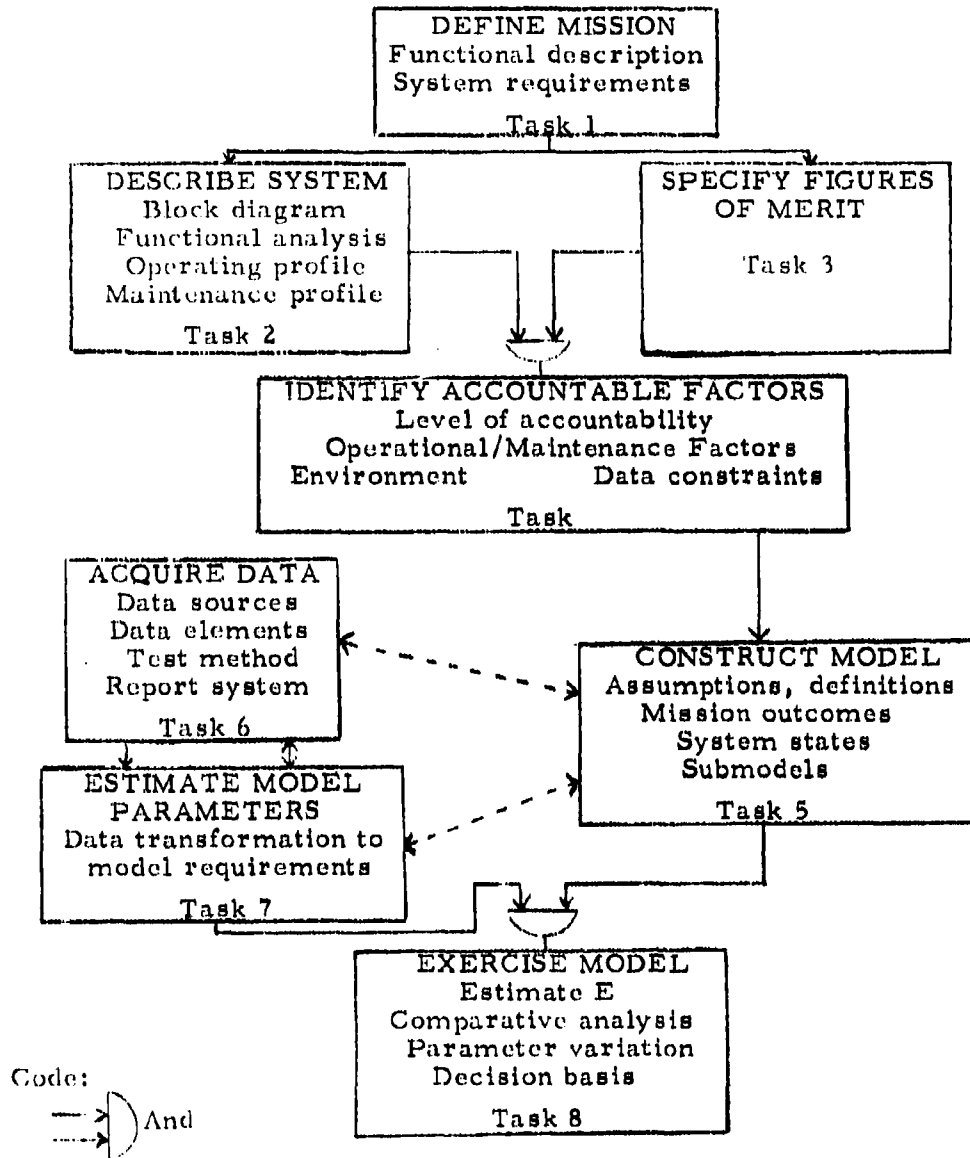


FIGURE 16

EIGHT TASKS ESSENTIAL TO EVALUATION OF SYSTEM EFFECTIVENESS

## VOLUME III TECHNICAL SUPPLEMENT<sup>(4)</sup>

### 1. Abstract

The Technical Supplement is concerned primarily with four examples of effectiveness evaluations. The systems involved are: the avionics system in a tactical fighter-bomber (Example A); a squadron of intercontinental ballistic missiles (Example B); a fixed radar surveillance and threat evaluation system (Example C); and a spacecraft system (Example D). In addition to the variety of system types included, an attempt has been made to illustrate procedures employed at different program phases of the system life-cycle. The evaluation of the avionics system takes place during program definition; the ICBM squadron, during operation; the radar system, during definition and operation; and the spacecraft, during acquisition. Since evaluation during the Conceptual Phase will generally be based on a gross comparison with existing, similar systems, it was not felt that an example of such an analysis was necessary. Further, each example is intended to illustrate to a different level of detail, various aspects of the evaluation. The avionics system example, for instance, shows the possibility of combining independent evaluations of several subsystems. The radar example shows simplifications which can be made in order to minimize the number of system states to be considered. In the ICBM example, illustrations of many of the detailed procedures required to evaluate components of the vectors and matrices are shown. Finally, the spacecraft example addresses itself to techniques for determining elements of the dependability matrix. It is stressed, however, that these examples do not purport to illustrate all possible methods of application and use of the evaluation procedures. Rather they are intended to show some methods for applying the concepts, areas of flexibility in their application, and some uses which might be made of the evaluations.

### 2. Summary

Short resumés of the examples presented in Volume III of the Task Group II report follow.

Airborne Avionics System Example The purpose of this example is to demonstrate how the effectiveness evaluation techniques proposed by Task Group II may be applied to the avionics system of a tactical fighter-bomber aircraft. The example considers only the "bombing" function. Similar analyses could be made for its "fighter," "ground support," etc., functions.

It is assumed that the effectiveness evaluation is being made during the Program Definition Phase of system life. Similar evaluations in the real world would also be necessary for system configurations established during the Acquisition and Operational Phases. A major consideration of the Program Definition Phase is "force structure;" i.e., the number of systems (aircraft) required to accomplish a specific mission. The example illustrates how the results of the effectiveness evaluation aid in making trade-offs and ultimate decisions.

The criterion of effectiveness is as follows:

- At any random time when an execution order is received, the aircraft shall take off immediately, receive a target assignment, proceed to target area, deliver weapon within 500 feet of target, and return to assigned operation base.

ICBM Fleet Example It is the specific object of this example to illustrate the analysis of an ICBM fleet in terms of the formal mathematical structure adopted by Task Group II of the WSEIAC. In particular, the analysis illustrates the usefulness of models in assessing the impact of potential system alterations.

The criterion of effectiveness for this hypothetical system may be stated as follows:

- Any missile of the ICBM fleet should be ready to accept a launch directive at a random point in time, or at an arbitrary time after an alarm condition has been established at a random point in time. It should then launch successfully within a prescribed reaction time, fly a

ballistic trajectory, penetrate enemy defenses, arm, fuse, impact within the prescribed target area, detonate and yield as planned with a prescribed probability of target destruction.

Minimum acceptable and objective numerical system requirements for availability, countdown, flight, and probability of kill are postulated in the form of an SOR.

Radar Surveillance System Example This example illustrates for this type of defense system specific recommended effectiveness prediction techniques. The tasks required to evaluate system effectiveness are considered for the four phases of system life, and the increasing amount of detail which is necessary as the system evolves is shown.

The requirements of this system are:

- detect airborne objects in the surveillance sector at a range of not less than 3,000 nautical miles
- identify the objects, and determine within 30 minutes whether or not they constitute a threat.

Spacecraft System Example This example illustrates in some detail a method by which the dependability of a spacecraft may be determined from conservative estimates of hardware reliability. This approach is recommended when only small amounts of test data on the vehicle are available. This usually occurs during the Program Definition and early system Acquisition Phases of programs on new systems. It is also useful for evaluating extremely costly systems of which only a few are to be constructed. No effort is made in this example to treat availability or capability, beyond illustrating their tie-in with dependability to calculate effectiveness.

The assumed purpose of this evaluation is the determination of critical elements in the proposed spacecraft configuration. The criterion of dependability for this system is as follows:

- The spacecraft system shall be capable of placing a

variety of payloads, including multiple satellites, into precise orbits about the earth. It shall have the capability of restarting in space after a sufficient coast period dependent on the specific payload and attitude orientation in space. The system shall be designed as an upper stage rocket propulsion vehicle.

## C. TASK GROUP III, "DATA COLLECTION AND MANAGEMENT REPORTS"<sup>(5)</sup>

### 1. Abstract

The report discusses the acquisition, control, reporting, summarizing and retrieving of data as it pertains to system effectiveness. Section II provides a summary of the main body of the report, which comprises Sections III, IV and V. Section III covers data acquisition and data elements in detail. Section IV discusses a System Effectiveness Information Central (SEIC) and a System Information Bank (SIB) for System Project Office use, and in addition, presents some of the problems on information retrieval. Section V discusses Management Summaries, and gives many examples and suggestions on how to present summarized data. Numerous conclusions and recommendations resulting from the efforts of Task Group III are incorporated as Sections VI and VII. The three appendixes to the report contain respectively, samples of reporting forms, a survey of languages and systems for information retrieval, and examples of proposed system effectiveness matrixes.

### 2. Summary of Section on Data Acquisition

Initially, the groups identified and defined generated raw data elements fundamental to the many disciplines (i.e., reliability, maintainability, repair actions, personnel subsystems, etc.) inherent in evaluation and measurement of system effectiveness and basic to the mathematical models and measurement of system effectiveness. Although the data elements identified are essentially those relating to missile site or squadron activity, they are easily translatable into comparable actions in support of aircraft or electronic systems/equipment and are considered minimum requisities for developing system effectiveness.

Matrices have been designed to display:

- raw data sources
- data recording forms
- data collection/reporting systems and controlling agencies
- field-generated versus computer-generated data
- current data collection/reporting systems coverage.

Analysis of these matrixes served to identify and highlight major problem areas inherent in the data acquisition systems presently used in industry and the Air Force. Some of the more obvious deficiencies are:

- (1) Certain needed data elements appear in all data systems, but many needed data elements appear in one and in no other system.
- (2) Some systems record and report essential data relating to time increments (i. e., AFSC Form 258 used mainly within AFSC), but most systems lack these elements.
- (3) Many required data elements are never reported outside of base level or contractor plants.
- (4) Some units report data elements only to their major using command.
- (5) AFM 66-1, Maintenance Data Collection System (MDCS), requires only certain data from AFTO Forms 210/211 to be reported to AFLC.
- (6) During the Acquisition Phase, many data elements are available only within contractor plants.

Some other problems require elaboration. First, in any data system one must minimize the administrative or clerical burden placed on the technician, either in the field, or at the factory or test site. To this end, various systems/procedures were examined to determine the most effective yet economical method in both cost and manpower, for assuring that all necessary and accurate data are obtained from the field. The approach which appears most feasible and promising to solve the short term acquisition problem is assignment, by the command having engineering responsibility, of a systems data specialist equipped with microfilm equipment to using command bases employing selected weapon systems. His function would be to obtain a microfilm record of all pertinent data produced in support of the specific weapon system and periodically submit for

processing, storage and analysis the film record to a designated information center, such as the System Effectiveness Information Central (SEIC) or System Information Bank (SIB), which are described in detail in this report. Validity, accuracy, and completeness of data could be determined in a timely manner by this individual on site. A major problem presently existing relative to error audit and resultant loss of important data and time from omissions on submitted data would thus be eliminated. The procedure outlined above would also provide a means of closing the loop on raw data retrieval and dissemination, an action which presently is almost nonexistent. Further, this would provide the means for indefinite retention of that data considered pertinent for selected, or designated, weapon systems.

Another problem is that the present Air Force and major command directives and procedures now permit no flexibility in records retention; e.g., field organizations are authorized to destroy AFTO Forms 210, 211, 212, etc., after a period anywhere from two to six months. When one recognizes that only a portion of the data generated and recorded on AFTO Forms 210/211 is transmitted to the AFLC AFM 66-1 data repository, it follows that much potentially valuable and pertinent information, from the viewpoint of the developing command, is not retained for the life of a weapon system.

Finally, the problem of adapting the AFM 66-1 Maintenance Data Collection System (MDCS) to provide all required system effectiveness data and information has been considered. Many different government agencies, groups, and committees are presently attempting to align or adapt their data collection systems to AFM 66-1. Headquarters USAF had designed and operated the AFM 66-1 MDCS for a specific and limited purpose; i.e., to provide maintenance man-hour accounting and logistics information to base maintenance management and AFLC. In these areas it has been a step in the right direction and a needed service. However, it is considered neither practical nor economical to reorient this program solely as a system effectiveness information system. Rather, the Air Force should continue to use it as initially conceived, with modifications, and incorporate it into the System Effectiveness Information Central as one of the many system data banks or information centers to permit drawing upon its capabilities.

### 3. Summary of Section on Data Central System

With the increasing complexity of modern systems, the need for system effectiveness information has also become more critical. Specialized information systems have been devised to respond to these data needs, but in general, they have been inadequate and particularly unresponsive to even minor changes in data requirements. The Air Force information system can perhaps be classified as a changing family of individual systems, each collecting and processing data in an individual way, rather than as a single integrated system. Information provided by those systems is primarily for use by those agencies for which the systems were designed.

At the same time, the Air Force information requirements make unreasonable demands on these unintegrated systems. The two main problems are (1) flexibility of type of information and (2) speed of response. A solution to these problems is a System Effectiveness Information Central (SEIC) controlling one or more System Information Bank(s) (SIB's) into which raw data are fed. The purpose of the SEIC would be to define data collection terms, products produced, agencies responsible for collecting, processing and retaining data, and the methodology and equipment used in the system. Communications entry into the various agencies and their data repositories (hereinafter referred to as system data banks or information banks) is required. The SEIC, in essence, would maintain a comprehensive index of pertinent information and have the communications wherewithal to extract data from the various system data banks. These data would be consolidated into periodic, one-time or special system effectiveness reports for use by various levels of management.

Maximum utilization should be made of present and future computer system techniques to process, analyze, and produce desired reports for any Air Force or industrial agency authorized access to the information. The ultimate goal would be an all-knowledgeable, all-responsive source of factual information concerning the many disciplines bearing on system effectiveness. The desired information should be available either within the SEIC central repository or the System Information Banks.

To attain the ultimate goal, a two-step approach is recommended. First, a pilot phase, SEIC I, would be applied against a selected weapon system; e.g., Minuteman Wing VI. The pilot phase would consolidate the procedures of agencies presently engaged in diverse but closely related data retrieval and processing actions in support of the selected weapon system, and "debug" the proposed methodology and techniques. Concurrently, the second phase, SEIC II, would start and would develop procedures for application on a larger and more comprehensive scale on future systems.

The agency established to operate SEIC II should be a pure "service" organization, established to provide system effectiveness information service to all USAF commands and aerospace industries. Its only mission in life would be the processing of system effectiveness information. Conceived as initially being under the operation and control of AFSC, SEIC II could be operated under the control of DOD should it be desired to expand the system to include other military and civilian agencies. Much detailed effort remains to bring to fruition this proposal. However, the principles and techniques presented are within the "state-of-the-art."

#### 4. Summary of Section on Data Management Reports

Information derived from review of various USAF and major command management reports requirements, discussions with industry and Air Force major command representatives, and discussions within WSEIAC imply, perhaps erroneously, that both industry and Air Force management have in the past concentrated primarily on only two types of status reporting in the design and development of weapon systems; i.e., cost and schedule. This concentration has highlighted such techniques as PERT, PERT Cost, Cost Planning and Appraisal, etc. While cost and schedule deserve this attention in both Air Force and industry, there remains an urgent need to develop similar control over the area of technical performance, not only in design and development (Acquisition Phase), but also in the operating environment (Operational Phase) of the system life-cycle. Technical performance seemingly becomes of major concern only at such times as inadequate performance factors (i.e., hardware reliability, CEP, etc.) occurs relative to the estimated/projected figure of merit at the particular time in

question, or following turnover of an operational element of the weapon system to the using command. It is recognized that a continual interplay of cost, schedules, and performance activity exists and must be displayed in an integrated fashion in any management reporting media.

From the development standpoint, hardware reliability to the exclusion of other supporting disciplines, alone appears to have been the major criterion upon which the degree of effectiveness has been measured. From a using command viewpoint, in-commission or availability and capability to successfully countdown to launch-commit appear to be the major criteria for measuring effectiveness.

In summary, only recently has Air Force management concerned itself with a simultaneous review of all elements essential to assessing system effectiveness. Further, industrial management has been primarily interested in developing those techniques which the Air Force has stressed in order to respond effectively to one-time and recurring data requirements or schedule position.

With this background in mind, Task Group III has approached the management reporting format objective from the viewpoint of compiling as a consolidated report -- for comparison purposes -- not only major cost and schedule information but also the key characteristics comprising figures of merit for system effectiveness. It is the interaction and interrelationship of these figures of merit that have an impact on whether the weapon system and its subelements are measuring up to the initial SOR and revised SPP requirements at any point of time in the life-cycle.

The management status reports devised by Task Group III and displayed in Section V and Appendix III allow:

- two levels of detail:
  - total system and subsystem, and
  - within each subsystem by hardware end items;
- narrative explanations where indices regress from the previous report;
- trend charts; e.g., reliability growth curves.

The System Program Office and contractor would execute all reports through the Acquisition Phase, while the operating command would provide all information during the Operational Phase. Since the intent is not to eliminate present reporting requirements, managers would usually require the kind and amount of information now being supplied. The report would extract and compile pertinent (top layer) information into an overview of the entire weapon system cost, schedule, and technical performance factors for ease of visibility and comparison at any level of management desired.

Initial progress has been made in identifying key system effectiveness figures of merit. However, additional study is required to identify comprehensively the total package for use of top management. Some characteristics already identified and deemed essential may eventually be replaced by items considered more critical. These proposed reports are compatible with the new Materiel Program Codes (MPC) used in current budget, program, and accounting procedures, and thus provide a common thread of data from conception through operation of the system.

Because these management reports represent a wide and diverse collection of information from both contractor and government sources, it may be impractical to grant all contractors the full scope of such reports. Thus, the principle would be established to provide each contractor only that information pertaining to his own activity. The Materiel Program Codes are especially valuable in this connection because they are structured at the first level of indenture by prime and/or associate contractors.

D. TASK GROUP IV, "COST-EFFECTIVENESS OPTIMIZATION"

VOLUME I  
SUMMARY, CONCLUSIONS, RECOMMENDATIONS<sup>(6)</sup>

1. Abstract

The underlying principles associated with cost-effectiveness analysis are discussed. The rationale, purpose, methodology required, and nature of the results that can be obtained by means of the analysis are presented in summary form. Illustrations of the type of input data required and the logic associated with its application are provided. The summary constitutes an overview of the more detailed task analysis and supplementary technical material presented in Volumes II and III. Included are the conclusions and recommendations as set forth in Volume II.

VOLUME II  
TASKS AND ANALYSIS METHODOLOGY<sup>(7)</sup>

1. Abstract

The report discusses the philosophy of cost-effectiveness and techniques for trade-off and optimization studies. It lists and discusses twelve tasks necessary to perform a cost-effectiveness analysis. A methodology is outlined for identifying and standardizing cost and effectiveness factors. Descriptive analytical models for cost-effectiveness are provided, including discussion of their sensitivity and validity. One section defines and discusses risk and uncertainty and their effect on the decision making process. Included is an extensive bibliography on cost-effectiveness. Examples of some of the techniques are covered in detail in a "Technical Supplement," which is Volume III of the final report of Task Group IV. Abstracts of these examples will be found in the Appendix of this report.

2. Overview

A major management goal throughout the life-cycle of a system -- from the Conceptual Phase through the Operational Phase -- is to exercise management control for the purposes of selecting, developing, and using systems in an optimum manner. The process by which management

is provided inputs for these types of decisions has been commonly called cost-effectiveness analysis.

Effectiveness is a measure of the capability of the system to accomplish the mission objectives. Cost-effectiveness studies are concerned with achieving a combination of resource-use and attained effectiveness that is best according to a selected criterion. Resource-use represents the expenditure of dollars, manpower, material, time, etc., required for the development, operation, and support of a system. We shall interpret such studies as an attempt to quantify how much it costs to achieve a certain effectiveness in order to select among a set of alternatives.

There is a recognized need for such studies. The enormous responsibility of the Department of Defense and the military services for maintaining a strong posture involves considerable expenditure of national resources. This is clearly evidenced by the proportion of the federal budget now allocated to defense. It is thus mandatory that the military authorities exercise maximum control in their planning, procurement, and operational activities in order to minimize the burden placed on the economy without any sacrifice in over-all defense goals.

Cost-effectiveness analysis is not new. It has been a part of military planning for some time, but the complexity of the military tasks now requires a multidisciplinary approach. The major utility of cost-effectiveness analysis is to provide management with the necessary information for decision-making purposes utilizing all the available knowledge and data in as efficient and complete a manner as is possible. Consequently, a demand has been created for improved analytical methods, better and more complete data, expanded computational capacity, etc., which has improved and will continue to improve management's capability for making good decisions.

### 3. Levels of Cost-Effectiveness Analyses

There are several decision making levels at which a cost-effectiveness analysis can be meaningfully applied, and these roughly correspond to the phases during system development. One level for

application is at the Required Operational Capability (ROC) level, formerly called the General Operational Requirement (GOR) phase. The ROC established a spectrum of objectives or missions. By considering over-all defense goals, the geopolitical and environmental factors, and the economic and technological capabilities, a particular mission or objective is selected. This level of application is generally coordinated at the DOD level.

After mission requirements are set at the Specific Operational Requirements (SOR) phase, there exists the need for selecting alternate or competing systems. Application of cost-effectiveness analysis at this level is primarily the responsibility of the military or procuring agencies.

A third level of application occurs during the development and operation of the weapon system. This level of application furnishes information for optimal use of resources within the constraints of mission and system requirements.

As a simple example of these levels the first would be concerned with such problems as optimum force-mix; e. g., expanded bomber-force size versus expanded missile-force size. The second level would be concerned with such combinatorial choices as pertain within a class of systems; e. g., within missile systems we may examine liquid versus solid fuel, tandem versus parallel stages, or soft versus hardened sites. The third level would be concerned with more detailed decisions within a given system configuration; e. g., for a missile one might evaluate pressurized or pump-fed propellant-loading systems, various stage diameters, various area ratios of engine nozzles, checkout and monitoring procedures, and the like.

This report is concerned primarily with the third level of analysis and, to a lesser extent, with the second level, in presenting and illustrating the concepts, methods, and procedures of cost-effectiveness analysis.

#### 4. General Concepts

To introduce the general concepts of a cost-effectiveness analysis, we shall interpret such analysis in the simplest of terms -- namely, the attempt to quantify how much it costs to achieve a certain effectiveness in

order to select among a set of alternatives. Cost is used to represent the amount of resource expenditure, and effectiveness is a measure of the system ability to accomplish its mission objectives.

The general approach for making such decisions consists of the following steps:

- (1) Define criteria for selection
- (2) Generate alternatives that satisfy operations requirements and constraints
- (3) Compute resultant values of cost and effectiveness for each alternative
- (4) Evaluate results with respect to the decision criterion.

Each of these major steps is discussed in detail in the report. It is worthwhile, however, to set the stage for such discussions in this introduction.

The criterion for selection must be one that is mission responsive, that is, it must answer the right question. Essentially, the criterion is based on maximizing effectiveness for a given cost or, conversely, minimizing cost for a given level of effectiveness. The criterion, however, must also define the level of analysis as discussed previously in this introduction and also the scope of the analysis in terms of resource, system, operational, and support constraints. Thus, the two basic criteria listed above may evolve into a criterion such as one to maximize effectiveness per dollar, provided effectiveness is greater than  $E^*$  and cost is less than  $C^*$  (where  $E^*$  and  $C^*$  refer to specific limiting values).

In generating acceptable alternatives, identification of all variable and fixed factors and their costs is required. In addition, the elements of risk and uncertainty as related to these factors and costs and the analysis of effects on other programs must also be considered. Such factors as availability of appropriate data, computational capacity, and restraints in time and effort available for the analysis will play important

roles in this phase. A generated alternative is then an acceptable combination of the selected factors with associated risk and uncertainty elements.

Measures of cost and effectiveness for each design alternative must then be computed. The form these measures take is related to the decision criterion. For effectiveness, the measure can range from a simple probability numeric, to an expected value, to the complete distribution of some over-all performance characteristic. The effectiveness model is based on sub-models for reliability, maintainability, and performance. These, in turn are based on the variable and fixed factors to be considered such as failure and repair distributions, internal stresses, environment, and design integration.

The cost measure must be one that can treat the major types of resource expenditures on some common basis. Sub-models are required for development costs, operating costs, and support costs both in terms of dollars and schedules. In addition, the burden a particular alternative places on other systems and objectives must be evaluated for a complete cost model.

The integration of the separate cost and effectiveness models into a single cost-effectiveness model provides the basis for decisions. It is at this stage where optimization theory becomes applicable, involving such disciplines as mathematical programming, stochastic process theory, calculus of variations, econometrics, and decision theory.

All of the above models must satisfy characteristics related to adequacy, representativeness, consistency, sensitivity, plausibility, criticality, workability, and suitability. These characteristics are discussed more fully in later sections. In applying the model, it must be emphasized that results of the optimization process can only indicate the best decision within the simplifications, assumptions, restrictions and omissions that were required to circumvent such problems as uncertainties, non-quantifiable factors, and inadequate data, time or computational capacity.

Thus, the cost-effectiveness analysis will usually yield only

partial analytic solutions. However, the framework for a final decision is provided. The cost-effectiveness analysis has reduced the guess work and intuitive estimates of cost and effectiveness, but the initial results must still be critically evaluated and combined with relevant political and timing factors by a judgment of the decision maker.

### VOLUME III TECHNICAL SUPPLEMENT (8)

#### 1. Abstract

A discussion of optimization is presented which amplifies the material in Volume II, Section IV. Optimization principles, criteria and checklists, as well as a summary of various applicable techniques is included. A series of six examples are described covering a number of critical aspects of cost-effectiveness analysis in considerable detail. Treated in the examples are: (1) Optimization of effectiveness based on reliability, maintainability, performance, and cost; (2) Allocation of reliability requirements among subsystems; (3) Payload allocation among three subsystems based on a fixed weight constraint; (4) Determination of best checkout routine for a duration constrained pre-launch test; (5) Optimization of availability for a system; and (6) Trade-off study between site hardening and dispersal for a missile system.

#### 2. Summary

The examples presented in Volume III of the Task Group IV report are summarized below.

Aircraft System Optimization A system cost-effectiveness model is developed for an Air Force training base at which daily bomber training flights are made. In the event of enemy attack, the base bomber force is assigned to targets. The objective of the example is to illustrate the optimization of the bomber effectiveness by trading off reliability, maintainability, performance and cost factors. The system effectiveness model is developed along the mathematical lines presented by Task Group II in Volume II<sup>(3)</sup> of their final report. Optimization is accomplished by computing and comparing the costs of eight possible measurement and support

policies in terms of two alternative figures of merit.

- For each target, there will be a 0.95 probability that at least one of the attacking aircraft will successfully accomplish the bombing run.
- There will be an average success probability of 0.95 for all assigned targets.

A significant aspect of this example is its illustration of the need for re-evaluating the criterion for optimization in terms of the realized output of the evaluation effort.

Reliability Allocation A method for allocating system reliability requirements among subsystem (or lower level units) is presented. The method considers serial and redundant interconnections among the subsystems. The relationship between system reliability requirements and system effectiveness requirements is considered.

Ballistic Missile Payload Allocation Each element of a ballistic missile's payload -- warhead, guidance and penetration aids -- will increase in effectiveness with an increase of weight allocated to the element. For a missile that is to be employed against a defended "point" target, this example presents a method for determining the optimum division of the missile's payload between the three competing (for weight) elements, when their individual weight-effectiveness relationships are known. For the case of a single missile per target, using a most basic application of the step-wise optimization philosophy of dynamic programming, the problem is formulated as a two-stage weight allocation process. The first stage determines the optimum trade-off between warhead (lethal radius) and guidance (CEP); the second stage determines the optimum division between penetration aids and an optimum mix of warhead and guidance. The same optimization process is useful for the cases of sequential and simultaneous multiple missile employment per target. Although this design optimization problem can be solved, functionally, for the modes of missile employment considered, its applicability to a real allocation problem is confounded by the design, intelligence and employment estimates required in the analysis. Use of this

method could show, however, the influence of the estimated uncertainties on the optimal payload division and could thereby serve as a useful point of departure for design compromises.

Optimizing a Pre-Launch Checkout This example presents a procedure for determining the optimum test content of an ICBM pre-launch checkout that is subject to a time constraint. Cost considerations are not introduced as a constraint, but instead are employed after the test content has been optimized for each possible test duration constraint in order to select between designs. An example is given and references are cited that contain an explanation of the estimation of the parameters associated with the design technique.

Missile Availability The availability of a system subjected to a sequence of calendar spaced checkouts is considered. Formulae for calculating the optimum frequency of checkout are given for the situation which considers checkout time as down time. Imperfect repair, imperfect checkout, and resource limitations are treated. A technique for the estimation of the parameters of the availability model is also given.

E. TASK GROUP V, "MANAGEMENT SYSTEMS"

VOLUME I  
SYSTEM EFFECTIVENESS ASSURANCE -  
SUMMARY, POLICY ISSUES, RECOMMENDATIONS<sup>(9)</sup>

1. Abstract

A system effectiveness assurance management concept is presented. It is based on the interacting process of experience retention (resources development) and program management technology (resources application). Six segments integral to this process are identified: data acquisition, technology development, personnel development, program planning, input surveillance, and output evaluation. The recognition and disciplined treatment of activities and elements critical to effectiveness included within each of the six segments of effectiveness assurance constitute the management system. Current practice of Air Force and industry is assessed, a group of fourteen basic policy issues are raised along with related recommendations, and an implementation plan is described.

2. Introduction and Overview

a. Scope A concept and philosophy of system effectiveness assurance management has been developed by Task Group V. On the basis of discussions, surveys and critical examination of the present status of effectiveness management throughout the Air Force and industry, the principal elements have been identified, policy issues have been raised, and an implementation plan recommended.

It is recognized that effectiveness must inevitably be treated as a quantitative characteristic of systems. Technical requirements, measurement methods, data elements, and cost-effectiveness analysis are essential ingredients. However, these aspects are treated fully in the reports of Task Groups I, II, III and IV. Task Group V has attempted to describe a management system that can form the basis for a new focus in the Air Force and industry through which major improvements in effectiveness can be achieved.

b. Emphasis on People Task Group V's general objective was to improve the system effectiveness assurance aspects of the Air Force management system. The purpose of any management system is to get things done through people. Consequently, this Task Group has endeavored to identify, develop and recommend methods for program management which will assure the achievement of system effectiveness objectives. An Air Force definition states that:

"Management is the process of developing and applying resources to accomplish pre-determined objectives."

This definition was adopted and used to further refine the Task Group V objective. The objective thus became "to help improve the Air Force resources development program and resources application requirements relative to those activities of people that are most critical to achieving system effectiveness." Emphasis has been placed on identifying qualified people as the primary resource for achieving system effectiveness. The importance of improving communications between the many groups whose skills must be utilized to achieve an effective weapon system has been stressed.

It was recognized that sanctimonious generalities about capable people, good communications and able management would not help. Therefore, strenuous efforts were made to be specific. The term "System Effectiveness Critical Activity" (SECA) was introduced and defined. A SECA is any activity that experience has shown must be subjected to formal discipline in order to ensure system effectiveness.

The term "discipline" is very important but subject to many connotations. To avoid misunderstanding, the Task Group equated discipline with all types of control over the activities of people. Specifically, it consists of:

- (1) training
- (2) motivation
- (3) command
- (4) audit

Again, the Task Group recognized that general comments on these four types of control over activities of people would not improve the system effectiveness assurance aspects of the Air Force management system. However, application of these general principles to specifically identified system effectiveness critical activities allows specific evaluation of current status and defines those areas where specific improvement actions can be introduced. For example, an Air Force program director may receive general training in program management philosophy but still be left in doubt about specific actions that he should take in managing a new program. By contrast, if he is taught that there is a tangible activity called "functional flow analysis," -- if he is provided with documented technology for this activity and motivated to apply it, -- if he is commanded by AFSCM 375-5 to require his contractors to schedule and fund the performance of this activity, -- and if the program is audited by his inspector general, there is a high probability that the activity will be accomplished.

The Task Group found it necessary to categorize activities of people into the following two types:

- (1) decision creation activities
- (2) hardware creation activities.

To assure system effectiveness, it is necessary to assure the quality of both decision making and hardware making. Assuring the quality of manual and machine activities that create hardware is the recognized purpose of AF/Industry Quality Control management systems, and Task Group V did concern itself with, and its recommendations do apply to, assuring the quality of hardware creation activities. However, the group's dominant effort was to define decision making critical activities and to contribute to resources development and resources application requirements for these activities.

c. Experience Retention For most critical activities, the primary source of knowledge is the operating experience of the Air Force and its contractors. It follows that resources development for these activities must exploit this experience. Task Group V identified and defined the critical activities in converting experience into resources suitable for application

to future programs. These steps are:

- (1) Data Acquisition
- (2) Technology Development
- (3) Personnel Development.

Collectively, these three steps constitute System Effectiveness Experience Retention.

d. Program Management Technology The resources application segment of the Air Force management system was identified with the procedures set forth in the AFSC 375 series documents. The term "program management technology" was introduced to represent all the formal disciplines for assuring effective application of resources for each activity critical to effectiveness. The basic steps in program management technology were identified as:

- (1) Program Planning
- (2) Input Surveillance
- (3) Output Evaluation.

Combination of these three steps with the three previously identified results in a six segment management system. The term "System Effectiveness Assurance Management System" (SEAMS) was introduced.

e. Status of Critical Activities Volume II of the Task Group V final report presents a series of surveys and discussions on the status of effectiveness management in the Air Force and industry. Additional discussions of some of the more significant aspects or elements of effectiveness assurance are also included. These surveys and discussions are arranged in general around the six formal segments contained in the broad management concept of Experience Retention and Experience Application listed in paragraphs c and d above. A summary of Volume II is contained in Section II of the report.

f. Policy Issues During the course of the detailed investigations and studies of the Task Group, a number of fundamental policy issues were identified. Appropriate consideration of these issues is basic to

further progress in the development of both technical and management aspects of system effectiveness. These policy issues are described in Section IV, and are the basis upon which specific recommendations and suggested implementation plans are developed in Section V.

g. Recommendations and Implementation Plan Although recommendations occur in many of the individual status reports and discussions of critical activities contained in Volume II, these have been summarized and in some cases generalized to form a consolidated group that are related to the major policy issues and to the six formal segments of the System Effectiveness Assurance Management System.

The Task Group did wish to assist the Air Force by doing some of the work proposed in the Recommendations Implementation Plan. However, such work could not be started until broad generalities and divergent opinions on assurance management had been converted into a concise, practical management system. Moreover, motivation of the Task Group members to implement their proposals depends on a thorough and positive evaluation of these proposals by the Air Force. It is important to recognize that SEAMS is a highly integrated system. It requires positive support by at least Headquarters USAF, AFSC, AFLC, ATC and AU. There would be little point in Task Group members contributing parts of the system if the whole is not acceptable to these Commands.

The Task Group recognizes that recommendations are useless unless opposition to their implementation can be overcome. Extensive opposition to any form of formalized experience retention does exist throughout both the Air Force and industry. The principal bases for such opposition appear to be:

- (1) fear that lessons learned will be expressed as rigid procedures that will restrict the exercise of judgment by new project organizations, and
- (2) the conviction of project managers and engineers that "my project is different."

Task Group V has developed and described logical and proven methods for overcoming both these types of opposition to formalized experience retention.

## VOLUME II ELEMENTS OF EFFECTIVENESS ASSURANCE MANAGEMENT<sup>(10)</sup>

### 1. Abstract

Volume II of the Task Group V Final Report presents summaries of many of the studies carried on by the Task Group during the six months of WSEIAC formal meetings and investigations. From these studies the concept and philosophy of a System Effectiveness Assurance Management System (SEAMS), the major policy issues, and recommendations presented in Volume I were developed. Air Force management of system effectiveness activities is assessed through surveys of some of the principal offices and commands. Industry capability for response to these new requirements is measured. A review of activities and discipline requirements essential to effectiveness assurance management in the context of the AF 375 series documents is provided. Finally, a series of studies and discussions of pertinent elements of system effectiveness is furnished, including a data control proposal, the effect of incentives, and appendixes on specification management, parts research and program management elements of the Conceptual and Definition Phases of system development.

### 2. Introduction and Summary

The volume presents reports covering the significant investigations accomplished by Task Group V. These studies, coupled with examination of relevant Air Force official documents and research reports and the many discussions held by task group members, were the principal basis for development of the effectiveness management philosophy, policy issues, and recommendations reported in Volume I of the Task Group V report.

a. Status Reports - Air Force Critical Activities Section II summarizes the principal findings resulting from the task group's appraisal of a number of Air Force organizations whose policies and practice have an overriding effect on system effectiveness. With the time available for the entire study, these appraisals could not possibly delve into great detail on

the organizations surveyed. However, there was a consistent thread of information that became apparent as the interviews continued. It is believed that the findings are quite representative of most comparable segments of the Air Force. Where possible, the appraisals were made using the six formalized segments of SEAMS as a checklist. Many of the policy issues and recommendations of Volume I were derived from these investigations.

b. Industry Attitudes and Climate In Section III of the volume a number of recent trends in industry that have a pronounced effect on system effectiveness are examined. Nine (9) specific items are discussed including: cost reduction, performance evaluation, weighted guidelines, time and cost, AF 375 series, Air Force program management, industry surveys, program definition, and allowable research. These recent trends constitute a climate within which industry is now operating. Finally, a list of ten (10) guidelines (and pitfalls to avoid) are suggested that have been found to be useful to industry in adjusting to these new trends.

c. Elements of Effectiveness Management Section IV of the volume provides a rationale for identification of activities critical to system effectiveness. These activities and their associated discipline requirements form the backbone of SEAMS. They are discussed in conjunction with some of the principal elements of the AF 375 series documents. Six steps (which constitute the Scientific Method) are reviewed as a suggested logical process for effectiveness analysis and problem solution. Some comments on organization for effectiveness functions are given.

d. System Effectiveness Information Central Both Task Groups III and V have recommended the formation of an Air Force centralized data and information service. The proposals of both groups recognize the need for a consolidation of the many separate data systems -- for a central bank that will accumulate pertinent information relative to system effectiveness and make this fund of knowledge available for new programs.

Both task groups have considered the problem from a different perspective, and yet the recommended approaches have much in common. Task Group V has proposed an appropriate set of objectives for

such a data central, its proposed scope, organization, program and funding. A charter is also suggested. These are contained in Section V.

An important recommendation of Task Group V (contained in Volume I) is that a careful study of both task group recommendations, as well as presently existing data centrals, be made prior to implementation of any new program.

e. Incentives and System Effectiveness Section VI contains some commentary on the new incentives now appearing in Air Force contracts. Some of the possible advantages are mentioned along with the many pitfalls that may befall the government and the contractor if incentive mechanics are not carefully worked out and agreed upon prior to contract signing. As a technical requirement, effectiveness embodies many interrelated system characteristics. At present it appears that attention should be directed toward some of the principal elements of effectiveness, such as reliability requirements or service warranties, rather than toward the composite term.

f. Supplementary Studies and Reports The appendix contains three supplementary items pertinent to effectiveness management. Appendix I contains a detailed functional flow diagram depicting the system program management elements during the Conceptual and Definition Phases. Because of the early stage of development of the AF 375 series and subsequent pending revisions, Task Group V did not propose a specific revision to include elements of effectiveness management and assurance. However, it is obvious that the format now emerging offers a natural medium by which to recognize technical and management aspects of effectiveness assurance.

Appendix II provides guidelines for research programs directed toward new parts. It is clearly recognized that one of the building blocks of an effective system is the piece parts of which it is composed. All too frequently, in the past, major program delays and increased costs have resulted from use of an unreliable part or one on which too little information is known to allow proper application.

Appendix III describes the evolution of the reliability specification. Currently, there is a strong attempt to consolidate the many existing specifications on every conceivable facet of reliability into a very few basic triservice and NASA coordinated documents. A similar consolidation of specifications dealing with other disciplines encompassed by system effectiveness will mark the next trend. The experience of one company in combining, at the policy level, the activities of reliability, maintainability, human engineering, safety engineering, and value engineering is described.

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## REFERENCES

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| <b>13. ABSTRACT</b><br>The principal findings, conclusions, and recommendations of the five WSEIAC Task Groups are presented in summary form. The system effectiveness problem is examined in light of the task group investigations. A fifteen-step procedure for cost-effectiveness assurance is presented. Application of the method and results to be expected in each phase of a system life-cycle are described. The impact on existing disciplines is examined. A section (Appendix IV) of this integrated summary contains abstracts and summaries of each of the ten reports submitted by the five Task Groups. Appendix I contains a more detailed treatment of the fifteen recommended tasks. Appendix II presents an example of application of this methodology shown for a hypothetical system in the Conceptual Phase. Finally, Appendix III is a glossary of effectiveness/cost-effectiveness terms. |                                      |                                                                                                                                                                        |

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