A METHOD FOR DERIVING JOB STANDARDS FROM SYSTEM EFFECTIVENESS CRITERIA

VOLUME I

METHOD DEVELOPMENT

PREPARED FOR:

PSYCHOLOGICAL RESEARCH BRANCH (PERS-152)
PERSONNEL RESEARCH DIVISION
BUREAU OF NAVAL PERSONNEL

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Dunlap and Associates, Inc.
Western Operations
1454 Cloverfield Boulevard
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FOREWORD

This report summarizes work to date on developing a method for deriving job standards from system effectiveness criteria. It is composed of two volumes. Volume I describes the technical work in developing the standards derivation method. Volume II, which is classified confidential, reports application of the method to the AN/SPS-40 radar.[1]

The study was initiated under the auspices of Captain R. M. Stuart, and has been continued under Captain L. A. Wilder, USN, Director, Personnel Research Division, Bureau of Naval Personnel. Mr. Sidney Friedman, Head, Psychological Research Branch (Pers-152) is Scientific Officer and Contract Monitor is Dr. Martin Wiskoff. Generous assistance in data collection was provided by Mr. A. A. Sjoholm and Mr. W. Hopkins (Pers-153) and Dr. J. R. Curtin and Mr. S. J. Sokol (BuShips 742C). The project staff is grateful to RADM E. C. Ruckner, ACNO (Training) and Mr. J. J. Collins (OP-07T) for their support and interest in the study.

Responsible officer for Dunlap and Associates, Inc., is Dr. Joseph W. Wulfeck. Dr. Robert E. Blanchard has served as Project Director. Staff members for the study have been Mr. R. A. Westland, Mr. M. B. Mitchell, Dr. A. J. Hoisman, Mr. C. A. Brictson and Mr. A. M. Daitch.

Several Navy facilities were visited while selecting a test subsystem for use in method development and application and later during data collection and procedural verification on the AN/SPS-40 radar. The cooperation of those facilities was outstanding and their contribution to the progress of the study is gratefully acknowledged:

- Commander Training Pacific, San Diego
- Fleet Anti-Warfare Training Center, San Diego

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[1] Dunlap and Associates, Inc., Western Division, A Method for Deriving Job Standards From System Effectiveness Criteria: Volume II - Application to the AN/SPS-40 Radar (U), Santa Monica, California, December 1964 (Confidential).

- Fleet ASW School, San Diego
- Destroyer Development Group Pacific, Long Beach
- Commander Cruisers Destroyers Pacific, San Diego
- Deputy Commander, Operational Test and Evaluation Force Pacific, San Diego
- Fleet Training Center, San Diego
- Mobile Electronics Technical Unit No. 5, San Diego
- USS Hammer, DD-781, San Diego
- USS Perkins, DDR-877, San Diego
- USS Hull, DD-945, San Diego

SUMMARY

The cost and complexity of modern Naval systems and the increasing difficulty in achieving optimal use of Naval personnel and training resources establish the need for a method for determining objectively the level of personnel performance necessary to meet Naval system operational requirements. The purpose of this study was to develop such a method with a basic capability for:

- Deriving specific personnel performance standards with definable relations to ultimate system effectiveness requirements; and
- Determining the effect on system effectiveness of personnel performance levels that deviate from established performance standards.

To assist in formulating an approach to method development, existing methods and techniques for relating personnel performance to system effectiveness were appraised for relevance to the present study and were modified and extended as appropriate. Also to aid in approach formulation, a conceptual framework was developed that comprises a derivative and an integrative process. The derivative process involves determination of the personnel performance requirements (job standards) imposed by a particular system design on associated personnel/equipment functional units; whereas the integrative process involves determination of the degree to which a set of available personnel capabilities can fulfill stated system requirements and the effect on system operational goals of performance levels that deviate from established performance standards.

The method developed comprises a set of procedures for using analytic and probabilistic tools which organize system effectiveness requirements and other types of system descriptive data to enable determination of system-related personnel performance standards at a given level of specificity. The types of input data required by the method in its present form are: (1) operational requirements data, (2) system descriptive data, and (3) human capability data.

As conceived in the study, a job standard ultimately will be composed of a personnel/equipment functional unit, an accuracy/time requirement and a required probability of successful performance. In the study to date, effort has been concentrated on describing and organizing personnel/equipment functional units and in treating the probability-of-successful-performance component of the job standard. However, preliminary work has been done to explore techniques for incorporating performance time and accuracy as job standard components.

To employ the method, system data are used to construct graphic and mathematical models of system operation. The Graphic State Sequence Model (GSSM) is a diagrammatic representation of the system which identifies the various means by which system effectiveness requirements may be satisfied. The GSSM provides for determination of sequential relations among personnel/equipment functions by specifying the state of the system prior to and following each function. The graphic model allows for establishment of the personnel/equipment functional units (PEF Units) and supports determination of accuracy and time components of the performance standard.

The Mathematical State Sequence Model (MSSM) utilizes conventional probability theory to describe, in equation form, the mathematical relations among the units composing the GSSM. Since effectiveness requirements are generally established for overall system operations or major system functions, standards derivation becomes a process of allocating those effectiveness requirements among personnel/equipment functional units (the derivative process). An interim allocation technique was developed which employs pooled, experimentally-derived data on human reliability to (1) determine the relation among the personnel/equipment functional units composing the system and (2) to establish the probability component of the job standard through the mathematical process.

To extend the basic capability of the method, two other problem dimensions were considered: (1) personnel performance standards for maintenance activities, and (2) additional job standard components (time and accuracy). It was determined that maintenance actions can be modeled using the graphic and mathematical state sequence modeling techniques of the basic standards method. Overall maintenance time requirements can be derived readily from system availability requirements if system failure rate input data are available. The performance time component of the job standard can then be determined for various categories of system maintenance.

Some hypotheses were developed regarding the relations between probability of accomplishment and the two additional job standard components, time and accuracy. Those relations are presented as a set of equations interrelating an Index of Task Accomplishment (IOTA) and the probability, time and accuracy components of the standard. While application of the equations is straightforward, it was emphasized that their use depends upon (1) experimental determination of certain unknown human capability values and (2) verification of their validity by applying them to data gathered under controlled, observational conditions.

The method was applied to data obtained on the AN/SPS-40 radar subsystem to test and refine various elements of the procedures. It was determined that the method can be applied successfully to a subsystem such as the AN/SPS-40 radar and that is likely will be applicable to any Navy system for which the necessary input data are available. During the test application, a procedural format was developed to facilitate use of the method by skilled systems analysts.

Due to the capability of the job standard method (1) to derive system-related performance standards and (2) to test the effects of performance levels that deviate from established standards, the method has broad potential application in personnel research and as a general research tool in system design and development. Use of job standards as appraisal criteria that reflect actual system operational requirements in the areas of selection and training seems quite promising. The method also appears useful as an aid in developing occupational hierarchies for personnel subsystems. A preliminary investigation of the usefulness of the method for that purpose was performed in the present study. As a system design and development tool, the method has high potential value in trade-off analysis and in testing the compatibility of various system design concepts relative to specified operational requirements.

To extend and refine the basic capability of the job standards derivation method reported here, additional methodological research, empirical testing and consideration of practical problems of implementation and application is recommended.

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I. INTRODUCTION

A. Purpose

The complexity of modern Naval systems has made it increasingly difficult to determine the levels of performance system personnel must meet in order that the system as a whole can meet its assigned effectiveness goals. If personnel performance levels are set too low, system effectiveness is likely to be unacceptable; if they are set too high, the Navy spends more than necessary to select and train personnel to man the system. In the second case, at least, system performance is not degraded, although that is small consolation since the Navy does not have infinite resources and cannot afford overdesign.

The Navy has expended a great deal of effort to develop and improve techniques that reveal the what, when and why of personnel performance in Naval systems; however, little has been done to find a way of objectively relating quantitative levels of personnel performance to ultimate system effectiveness requirements. For the most part, subject matter experts make estimates of required personnel performance levels. In some cases, performance measures are obtained from a specific group of personnel who are presumed to have the skills and abilities that the system is thought to require, and the results are used to specify desirable personnel performance levels. That approach overlooks objective determination of the personnel performance the system requires and rests entirely on what knowledgeable people think it requires. Unfortunately, today's complex Naval systems cannot easily tolerate the risk inherent in the use of subjective criteria. Performance levels set in that manner may be too high, too low, or right on the button, but who is to know which?

To remedy that situation, a set of personnel goals or minimum job standards with definable relations to ultimate system effectiveness requirements is needed to provide a systematic basis for relating system performance requirements to levels of personnel performance. Such performance standards would provide objective, system-related criterion data to persons responsible for selecting, training and evaluating personnel.

In addition, a means should be available to estimate the extent to which system effectiveness would be affected by deviations from established performance standards. If it is determined that a group being considered for assignment to a system cannot meet a number of performance standards, it is important to be able to determine the specific effect of that particular personnel group's substandard performance on system operation. The results of such a test would provide an indication of the amount of degradation in system effectiveness that could be expected from assigning that group to the system.

Therefore, the purpose of this study centers around developing a methodology that would fulfill two objectives:

- Derivation of specific personnel performance standards with definable relations to ultimate system effectiveness requirements; and
- Determination of the effect on system effectiveness of performance levels that deviate from established performance standards.

B. Scope

Most complex method development studies can be viewed as continuous efforts with some reasonably well-defined milestones. The study effort reported here was devoted to developing a basic capability for meeting the two objectives stated previously. Our primary milestones were:

- Development of basic tools,
- Test applications of those tools,
- Refinement of the method based on findings resulting from application, and
- Consideration of additional problem dimensions to broaden the method's utility.

Generally, the effort has consisted of reviewing existing methods and techniques for relating personnel performance to system effectiveness and combining, modifying and extending those methods and techniques as required to quantify the relation between system processes and criteria of system effectiveness.

To insure that the method would have practical utility and to test its applicability empirically, it has been applied to the AN/SPS-40 radar which is an installed shipboard subsystem (see Volume II of the report). That application demonstrated the usefulness of the method as well as its present limitations. During that test application, a procedural format was developed for applying the method (see Appendix B). The procedural format permits use of the method by skilled systems analysts and does not require the use of advanced mathematics.

C. Products

Products of the study are:

1. A critique of the literature dealing with methods and techniques for quantifying the relation between personnel performance and ultimate system effectiveness requirements.
2. A method or series of procedures that provide for:
    a. Identifying personnel/equipment functional units composing a system or subsystem and defining their functional relation to required outputs.
    b. Stating the contribution of each personnel/equipment functional unit to system operation.
    c. Establishing performance standards for each personnel/equipment functional unit that can be related directly to ultimate system effectiveness requirements.
    d. Testing the effects on system effectiveness of performance levels that deviate from the established performance standards.
3. An empirical test of the adequacy and practicality of the method using data obtained on an operational Navy subsystem (AN/SPS-40).
4. A body of performance standards for the personnel/equipment functional units identified for the AN/SPS-40 test subsystem.
5. Preliminary investigation of the usefulness of the method as an aid in constructing occupational hierarchies (position definitions) using data resulting from the AN/SPS-40 analysis.
6. A procedural format that will permit use of the method by the typical systems analyst and which will not require skills in advanced mathematics.

II. APPROACH FORMULATION

Formulating an approach for developing a method for establishing system-related job standards involved two steps:

- Detailed examination of various existing techniques for identifying personnel/equipment system processes and for quantifying the relation of those processes with criteria of system effectiveness.
- Development of a conceptual framework for use as a specific guide for method development and to maintain continuity of purpose with study objectives.

A brief overview of related research and a detailed description of the conceptual framework for the approach are given below.

A. Overview of Related Research

In order to assay methods currently used to evaluate personnel performance and general tools of systems analysis, a detailed literature review was conducted focusing on existing system analysis tools and their application to military system analysis and evaluation. Over three hundred articles and reports have been reviewed. A detailed critique of the major studies has been submitted as a separate project product.[1] Principal findings and brief summaries of the more important literature investigated are reported here.

For convenience of reporting, system techniques are divided into two classes: techniques that are essentially conceptual or graphic, and those that are mathematical. Because of the special need of the study for quantifiable system measures, current emphasis in reviewing the literature is in the area of mathematical modeling techniques. That emphasis is reflected in both the number and kind of report reviewed.

A list of selected references including the citations referenced in this summary of the literature review, as well as other reports germane to the job standards subject area, is provided in Appendix A.

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[1] Hoisman, A. J., and Daitch, A. M. Techniques for Relating Personnel Performance to Systems Effectiveness Criteria: A Critical Review of the Literature, Santa Monica, California: Dunlap and Associates, Inc., September 1964.

1. Non-Mathematical Techniques

While the literature of system analysis and evaluation has a long and varied history (cf. Whitehead, 1925; Chapman, 1952; Hoag, 1956), it was not until the late 1950's that major effort was directed toward developing techniques of system analysis that were general rather than system specific. The most tangible evidence of heightened interest at that time may be seen in the work sponsored by the Office of Naval Research to synthesize systems research methodology (McGrath, Nordlie and Vaughn, 1960; McGrath and Nordlie, 1959; McGrath and Nordlie, 1960; and Havron, 1961). Although that ambitious program has identified many problem areas in the systems analysis field, no solutions that would have direct relevance to job standards methodology have been proposed.

Examples of specific methods of system analysis are the work of Bates, Schaeffer and Shapero (Shapero and Bates, 1959; Schaeffer and Shapero, 1961; and Schaeffer, 1962). The intent of their conceptualization is development of methods of analysis which will integrate human system elements with an overall system analysis. The result is an analytic instrument based on the Systems Analysis and Integration Model (SAIM) which consists of a comprehensive classification scheme of all major system elements presented in a descriptive matrix format. The matrix classifies the elements of a system into three groups: those determining the nature and form of a system; those comprising the parts of the system; and those integrating the parts of a system. Elements of the system are shown in a two-dimensional square matrix which lists system elements as row and column headings. Entries in the cells formed are used to indicate direct connections between pairs of system elements. The matrix may be re-entered as frequently as necessary to trace all meaningful (and practical) element interactions. The matrix produces a lattice of connections representing the total relation among the specified elements.

It is felt that while the SAIM may be helpful in some circumstances as a tool to isolate system goals most directly affected by human components (in a given system), its potential in system analysis seems limited to use principally as a descriptive technique. As such, there would appear to be no special advantage in its use over, say, a more diagrammatic technique.

2. Mathematical Models and Analytic Techniques

The systems analysis studies reviewed and summarized below may be categorized as dealing with performance, availability, or allocation of system requirements. The "performance" category may be classified as either human or equipment performance. Some of the studies that treat equipment performance could be adapted to treat human performance: they will be noted when appropriate.

a. Performance. The majority of the systems studies reviewed here dealt with analysis of performance and derivation of various performance measures. Siegel and Wolf (1961), Swain (1963), and Young (1962) were concerned with human performance. Siegel and Wolf developed a digital simulation model to evaluate man's performance in one-operator, man-machine systems. In their model, operator performance in doing a specific set of subtasks was simulated. They considered the effects of operator stress on speed and accuracy of subtask performance. Swain's work described a human factors analysis which derived a mathematical model of a man-machine system degradation resulting from human errors. His model allowed for computation of system or subsystem failures based on specified human errors. A novel approach to human factors analysis was discussed by Young who treated the problem of optimizing scheduling of crew members to tasks. He applied the classical assignment problem of linear programming to assign men to jobs on the basis of each individual's task proficiency.

The work of Hamilton et.al., (1960) bordered between human performance and system performance since they developed a relation between human operator variables and system performance variables. The system performance measure was the probability of the system successfully completing its mission (some may argue that this is an effectiveness criterion and not a performance measure, but in the context of Hamilton's report, it is a performance measure) and it was derived as a function of time remaining to complete the different tasks (detection, identification, etc.) that the operator performed.

Studies that dealt with equipment performance without regard a man-machine system context were reported by Engel (1963), White et.al., (1963), and Magnavox Research Laboratories (1961). Engel derived a mathematical model that could be utilized for estimating the tracking effectiveness of a surveillance force in continuous detection and tracking of hostile targets entering a surveillance region. His measure of performance was the proportion of targets that could be expected to be under surveillance or to be tracked at any instant of time. Although Engel did not mention human behavior specifically, the model could probably be adapted to human effectiveness for a manual surveillance/tracking mode. The work of White et.al., was concerned with computing equipment performance, using Figure-of-Merit (a performance assessment in terms of the user's requirements) as the measure of interest. They also did not treat human behavior, but their techniques could be modified to include it. The Magnavox study treated development of a mathematical model that could be utilized in design of information storage and retrieval systems. It derived the efficiency of a given component in performing a given operation and an efficiency matrix for a system composed of a specific set of components. Since a human can be regarded as a system component, the model could be adapted to include human behavior.

b. Availability. The majority of studies of availability measures fail to treat human performance aspects in quantitative detail. A study by Westland and Hanifan (1963) provides a compilation of availability models applicable to a variety of Navy missions. Krull (1963) developed analytical techniques that treated the problem of a system subject to failure and subsequent maintenance in which the failure rates and repair rates were considered to be stochastic variables. The system was composed of operational units and repair channels with time-dependent failure rates and repair rates, respectively. The model expressed the probability that a certain number of the operational units would be in commission at any time, and dealt with reliability and maintainability. Since repair activities of maintenance crews are human functions, the model can be regarded as including human behavior.

c. Allocation of System Requirements. The studies by Hamilton et. al., and Krull have utility for allocating system requirements to human performance standards. Hamilton et. al., developed a functional relation between the probability of a system successfully completing its mission and the time necessary to perform different system functions. If the probability of success is specified as a system requirement, the times to perform tasks or functions can be allocated. Those times could then be considered one type of job standard.

Krull's model expressed the probability that a certain number of system operational units would be in commission at any time, t. Such a measure can be regarded as an availability measure and it would be possible to use the model to express a maintenance time limitation on repair crews. For example, suppose that 10 units out of a total of 12 are operational at time, t_1, and it is necessary that 12 units be operational at t_2; the difference establishes a job standards requirement for the maintenance crews.

3. Remarks

No modeling and analytical techniques were found to be fully applicable in meeting the two methodological objectives of the present study. However, the concepts and techniques formulated by many of the researchers aided materially in the development of specific portions of the method reported here.

B. Conceptual Framework

The key to our conceptual framework is system mission and associated system effectiveness requirements. Several definitions of a "system" have been offered in the literature; however, they are generally inadequate for our purposes. It has been said that one man's system is another man's subsystem, and so forth. Therefore, after consideration of project scope and needs, classes of definitions and current Navy concepts, it was decided to define a system operationally as being at the level characterized by ASW, AAW, Attack or Logistics organizations. Any organization comprised of working units at the AAW, ASW, Attack and Logistic level would be considered larger than a system ... a "supra-system." Similarly, a major functional component of the level connoted by AAW, for example, would be considered a subsystem, such as a fire control radar subsystem or a SAM missile subsystem of an AAW system.

A derivative and an integrative process constitute the basis of the conceptual framework. The derivative process involves determining the performance requirements imposed by a particular design on associated interacting personnel and equipment functions; whereas the integrative process involves determing the degree to which a set of available personnel capabilities can fulfill those stated system requirements.

1. The Derivative Process

The mission a system is to fulfill gives rise to a body of system functions and a related set of system effectiveness requirements which define the necessary performance levels for those functions. We have selected the term Personnel/Equipment Functional Unit (PEF Unit) to describe a given man-machine functional interaction at any given level of specificity. The relation of a series of PEF Units, each of which includes a personnel and an equipment component (P_iE_i), to a system effectiveness requirement (S_r) can be expressed mathematically as:

$$S_r = (P_1E_1)(P_2E_2) \ldots (P_iE_i) \ldots (P_nE_n),$$

where n represents the total number of PEF Units in the system.

Beginning with an overall subsystem function or gross PEF Unit (e.g., detect airborne targets) and an associated performance requirement (S_r = target detection at 100 miles with probability .95), the derivative process simultaneously fractionates both the requirement (S_r) and the function (PEF Unit) from statements of gross relations to statements of sufficient behavioral specificity that the S_r/PEF Unit relation can be employed effectively in setting the standards of performance. At that level of specificity, an S_r associated with its related PEF Unit represents the performance standard.

The process of fractionating produces a network or series of traces which relate the specific S_r/PEF Unit statements to overall system effectiveness requirements. It is important to protect and sustain that network throughout the derivative process since the traces make it possible (1) to derive job standards that are related to system effectiveness requirements, and (2) to reflect variations in meeting job standards quantitatively in terms of overall system effectiveness. The purpose of the derivative process, then, is to define specific functional units with associated performance standards in a form usable by personnel subsystem designers and to establish a requirements/PEF Unit network as a basis for integrative processing.

2. The Integrative Process

The concept of an integrative process represents an attempt to explore fully the potential usefulness of the method in providing a means for testing the effect of a given system state, expressed in terms of a particular set of personnel capabilities, on specified system requirements. The integrative process can be described as:

$$(P'_1E'_1)(P'_2E'_2)\ldots(P'_iE'_i)\ldots(P'_nE'_n) = S_c.$$

The term S_c represents an estimate of system output resulting from performance of the related PEF Units. The personnel/equipment components of the PEF Units above are designated P' and E' to distinguish them from the derivative case, although they represent identical functional units.

The source of personnel capability data will depend upon the type of system, its state of development and the availability of personnel. If a personnel group exists and is being considered for assignment to the system (or must be assigned), capability data can be obtained through direct performance measurement. If there is no identifiable personnel group to permit collection of capability data, then it may be necessary to obtain the data through observation of proximate PEF Units on other systems, by simulation or from collections of behavioral data available in "data stores."

The integrative process involves assessment of PEF Units in terms of human capabilities. The process originates at the most specific

PEF Unit/S_c level and proceeds upward by integrating more inclusive PEF Unit/S_c statements until an S_c is obtained that is general enough to be compared meaningfully with an S_r. At that point, the adequacy of a given system design can be appraised in terms of the difference between the S_r and the obtained S_c.

In application, the integrative process would be used to test or to predict the contribution of a defined or postulated personnel group's capabilities in fulfilling system effectiveness requirements. That application would be useful in evaluating what one has, in terms of personnel capability resources, against what a given system configuration demands. The network of PEF Units then, has a transitive or feedback characteristic. It must support both derivation of specific S_r/PEF Unit relations and integration of PEF Unit/S_c relations.

3. Definition of a Job Standard

As conceived in this study, job standards would consist ideally of the following components:

	Example
Description of a personnel/equipment functional unit (PEF Unit) at a desired level of specificity including the action taken and the object of that action.	Amplifier balance adjusted to zero.
. Required accuracy	$A = \pm 5$ mv
. Required performance time to complete PEF Unit	$T = 0.5$ minutes
. Required probability of successfully completing the action	$P = 0.997$

The accuracy, time and probability components constitute the job standard, per se, and represent fractionated system operational requirements.

When combined for a given PEF Unit, the components would have the following relations:

	Example
. Time versus accuracy and/or probability, if applicable	$P = .997$ for adjusting to ± 5 mv within 0.3 minutes and to ± 3 mv within 0.5 minutes

. Accuracy versus probability, if applicable	P of attaining ± 5mv = .997 P of attaining ± 10mv = 0.998 P of attaining ± 15mv = 0.999

Within the context of developing a basic capability in the present study, emphasis was placed on treating the probability component and the PEF Unit. A discussion of the integration of time and accuracy components is provided in Section IV-B.

4. Input Data Required

It was determined that several types of input data would be required within our conceptual framework. Those data types are:

a. Operational Requirements Data

- Overall system effectiveness requirements
- Performance requirements for major functions
- Availability, reliability and maintainability requirements

b. System Descriptive Data

- System design data
- Development and test reports
- Operating and maintenance procedures

c. Human Capability Data

- Performance times
- Probability of correct performance
- Variability of performance

The availability of those various types of system data and the degree to which they can be specified will vary among systems according to the nature and status of the development effort. Operational requirements data are the most critical since they are the ultimate basis for all standards which are to be established. For operational systems, system descriptive data generally exist; the major task is that of extracting information from reports and records and supplementing that with shipboard inspections or visits to training centers. Human capability data, necessary for integrative use of the method, currently are not widely available in data store form. Until they are, that requirement must be filled by collecting performance data empirically on subject groups composing a specific personnel subsystem design.

III. METHOD DEVELOPMENT

The purpose of the study, as noted previously, was to develop a method that would fulfill two objectives:

- Derivation of specific personnel performance standards with definable relations to ultimate system effectiveness requirements, and

- Determination of the effect on system effectiveness of performance levels that deviate from established performance standards.

To meet those objectives it was required to develop a set of procedures and analytic or probabilistic tools which would take system effectiveness requirements and system design data as inputs and provide system-related personnel performance standards as outputs. Since effectiveness requirements are most frequently established for the overall operation of the system, standards derivation -- the first methodological objective -- becomes a process of allocating overall system requirements among personnel/equipment functional units. Essentially the same method must permit determination of the effect of a given personnel subsystem design on system effectiveness to achieve the second methodological objective.

As a first step in method development, the conceptual framework was used as a basis for establishing major procedural steps which during the course of the study were ultimately refined to the following:

1. Definition of system operational requirements.

2. Definition of functional unit levels of specificity.

3. Determination of relations among PEF Units through construction of graphic and mathematical models.

4. Allocation of overall requirements to subordinate elements to establish standards for all PEF Units.

5. Utilization of the mathematical model and derived standards to determine the effect of a given personnel subsystem design on ultimate system effectiveness requirements.

Steps 1 through 4 treat the derivative process while Step 5 is related to the integrative process.

In the sections below, the approach to method development and a description of the major steps are presented with a description of the various uses of kinds of input data listed in section II-B.

A. Definition of System Operational Requirements

System operational requirements constitute a quantitative description of what functions the system must perform, and how well it must perform them. Since they represent the ultimate scale against which system performance is measured, they are the logical choice as the basis for establishing objective standards for personnel performance.

Specificity in definition of the hierarchy of system requirements varies among systems, but the following are representative of those required to establish job standards:

- Overall effectiveness requirements (e.g., overall probability of accomplishing the mission for which the system was designed)
- Performance requirements for major system functions (e.g., for a radar system, time and probability requirements for detection and tracking would be included)
- Availability requirements (reliability and maintainability)

$$A = MTBF/(MTBF + MTTR)$$

where:

MTBF = Mean Time Between Failures
MTTR = Mean Time to Restore

An illustration of the relation among the various requirements for a radar system follows:

$$E = P(d) \cdot P(a) \cdot P(t) \cdot A$$

where:

E = effectiveness

P(d) = probability of detection (e.g., probability of detecting a $5m^2$ target at 100 miles)

P(a) = probability of altitude determination (e.g., probability of determining altitude within 1,000 feet)

$P(t)$ = probability of tracking (e.g., probability of successfully tracking the target)

A = availability (probability that the system will be operating at a specific point in time).

Additional data that could be used in establishing standards would be time constraints:

$$t_d \leq T_{d_{max}}$$

$$t_d + t_a + t_t \leq T_{s_{max}}$$

where:

t_d = detection time

$T_{d_{max}}$ = specified maximum detection time

t_a = altitude determination time

t_t = track determination time

$T_{s_{max}}$ = specified maximum time to perform all system functions.

B. Definition of Functional Unit Levels of Specificity

Within our conceptual framework for establishing performance standards, the PEF Unit has been defined as a man-machine functional interaction at a given level of specificity. At the most gross level of specificity, an illustrative PEF Unit might be "detection of a target." At a more elemental level, an illustrative PEF Unit might be "selection of a transmission frequency by positioning a selector switch." A PEF Unit specificity hierarchy of the following form serves as a useful framework:

- System Function
- Personnel Function
- Task

- Subtask
- Element

At various levels of analysis, the system may be described as consisting of x system functions, or y tasks, or z elements. While the PEF Units at the extremes of the hierarchy have been reasonably well defined, definition of the intermediate levels has been somewhat hampered by the variability of PEF Units found in various systems. To avoid the problem encountered in defining intermediate levels and testing for their existence in any specific system, our approach has been to identify the system function PEF Units as Level I, and subordinate PEF Units as Level II, Level III, etc. At Level I, system functions are generally designated by a brief noun title, such as "detection," "identification," or "inspection." Alternatively, exclamatory verbs hold equally descriptive communicative value, "detect," "identify," or "inspect." Each of those general categories includes PEF Units both necessary and sufficient to accomplish the system mission. In addition:

1. The system function is always immediately related to the system mission (i.e., no intermediary level of system operation exists); and
2. The system function is developed apart from and without regard to the specific hardware of the system being described. As a rule, systems with similar missions will have similar functions.

C. Graphic Description of Functional Relations

To develop an objective method of deriving system performance standards, a general approach was sought by which a mathematical model of any system could be constructed to describe the relations between definable PEF Units. It was recognized that before an accurate mathematical model could be produced, system information would have to be organized to show meaningful functional relations among comparable PEF Units. As a result, a diagrammatic modeling technique was developed. Since all Personnel/Equipment functions effect a change in the state or status of the system, PEF Units are graphically defined according to the states of the system just prior to and immediately following their occurrence. The technique of depicting a system in that manner produces a diagram which we term a Graphic State Sequence Model (GSSM).[1]

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[1] The GSSM is not to be confused with an operational sequence diagram (OSD) which stresses human decisions and actions rather than personnel/equipment functions which are defined by specific configurations of input and output states.

If we assume that the criteria for acceptable system functioning can be fully defined, including all tolerances and relevant constraints, a sequence of states can be generated by dividing the system into a patterned series of spacio-temporal units of performance (or PEF Units) so that one can describe completely the instantaneous, unchanging state of the system between each unit. That is, PEF Units are delineated by the static characteristics of the system at specified instants in time. In practice, however, it is impractical to describe all features of the system between each functional unit, particularly when there are many such units, each producing a relatively small change in the system. Instead, one need describe only those static characteristics relevant to each single PEF Unit. As indicated in Figure 1, the entire system can be viewed as a single PEF Unit; the input state defines the relevant system conditions immediately prior to operation initiation, and the output state reflects the mission requirements and system effectiveness criteria.

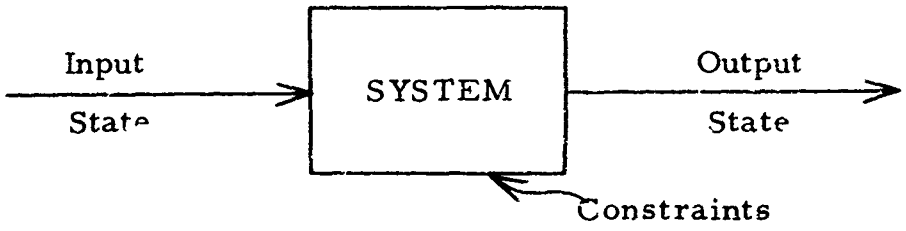

Figure 1. The system as a single PEF Unit.

Clearly, the very simple appearing model in Figure 1 describes the most complex personnel/equipment function. Conversely, as one examines the system in increasing detail and describes system operations in terms of more specific but less complex PEF Units, the GSSM grows increasingly complex. For example, Figure 2 is an illustration of a Level II GSSM. In that figure the receive and record activities of the AN/SKQ-1 [1] are shown to comprise three functions, I, II and III (i.e., three Level I PEF Units), each of which has been elaborated at specificity Level II, with PEF Units represented by the letters A through J. Further elaboration of the second level activities would result in a GSSM with a greater number of PEF Units and more complex interrelations between them.

However, no matter how detailed the GSSM, one must begin with a complete, objective description of the initial input state, final output state and constraints as depicted in Figure 1. The same diagrammatic approach is applicable in treating PEF Units at any level in the specificity hierarchy

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[1] A shipboard equipment for receiving and recording telemetered signals from Navy surface-to-air guided missiles.

from the highest (or Level I), to the lowest (or element) level which involves simple personnel/equipment operations; the performance standard method will generally require that the system be described to the element level.

Specific procedures for constructing a GSSM have been identified and are described in Appendix B. The technique utilizes concepts of symbolic logic commonly applied in computer design. The construction of a GSSM for the AN/SPS-40 radar presented in Volume II of this report and the model segments shown in the following sections illustrate the general use of the technique.

To construct a highly descriptive GSSM from system design data requires training and special caution. Of primary importance is the necessity to approach the job without bias; i.e., the GSSM must be developed such that it is minimally affected either by the system designer's concept of how the system is expected to operate or by information regarding the past performance of an operational system. By attending primarily to required input and output states -- rather than to the intermediate processes -- it becomes possible to consider all possible ways of getting from one state to the next. The technique allows a detached appraisal of system design since: (1) unexpected processes may emerge as real and viable alternatives to the one(s) intended; (2) omissions in design may be uncovered by observing the inadequacy of a state for initiating a PEF Unit; and (3) design weaknesses stand out when the analyst is forced to ask, "What condition(s) necessarily give rise to the next set of functions and how can we ascertain their occurrence?"

A significant contribution to method development was made by using the graphic modeling technique to define the elemental PEF Unit. By virtue of its objectivity, the logic diagram eliminates problems usually associated with reliance on behavioral data. Thus, it is possible to specify the characteristics of the elemental PEF Unit according to non-behavioral, relative criteria. The complete definition is presented in Appendix B.

The importance of delineating meaningful elements of system performance rests on the fact that human activity can be reduced theoretically to an underlying set of neuromuscular and molecular changes. However, one might spend much time trying to define a system at that level without ever arriving at a means for establishing standards. It is necessary, therefore, to state system behavior only to that describable and measurable level necessary and amenable to an effective methodology. In our approach, the element PEF Unit represents that minimum level; it is definable according to non-behavioral, relatively objective criteria relating to construction by logical diagramming. Any further attempt at moving to a

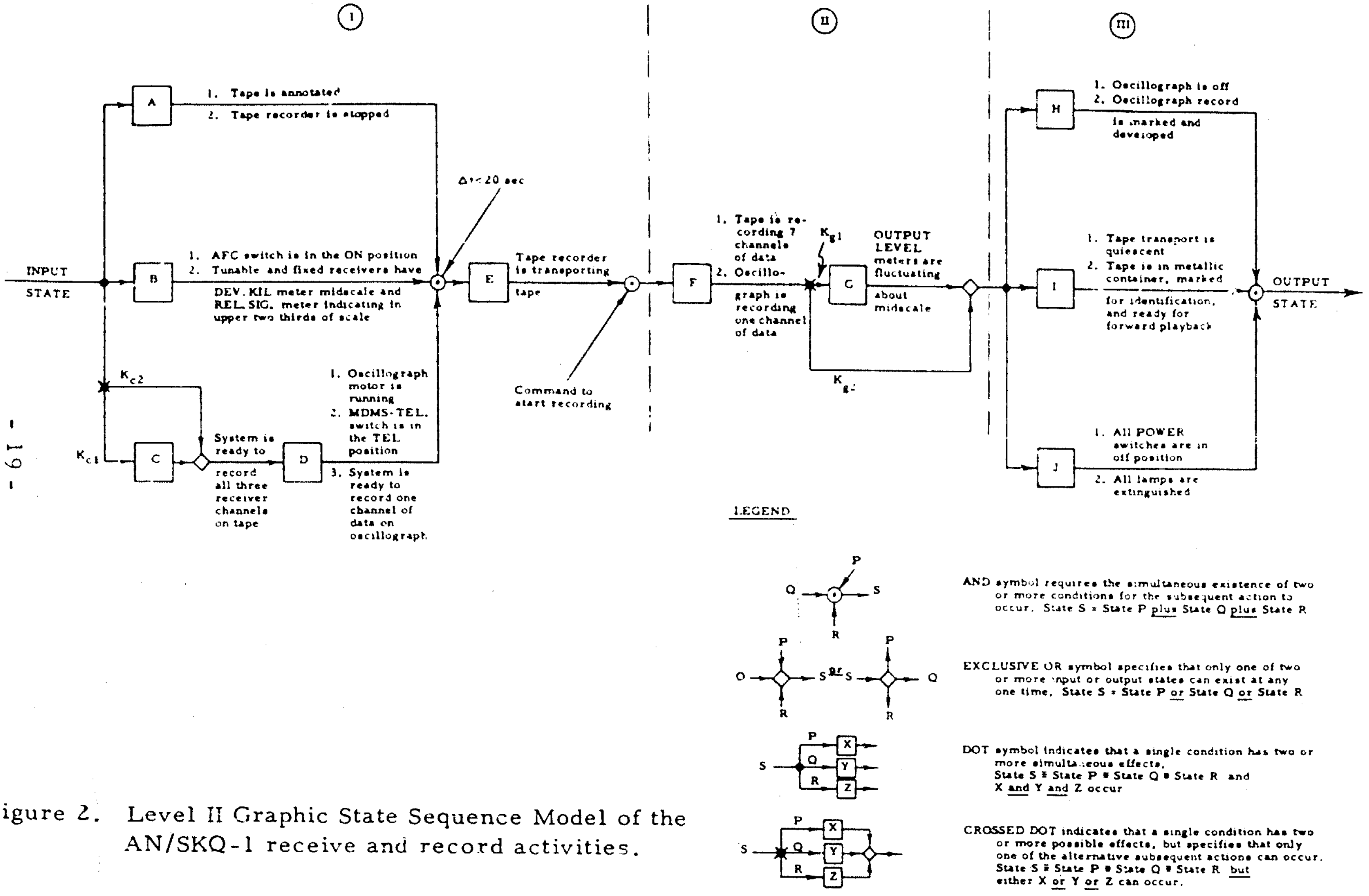


Figure 2. Level II Graphic State Sequence Model of the AN/SKQ-1 receive and record activities.

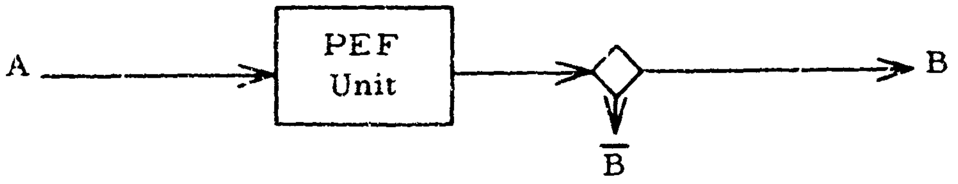
lower level would have no effect on the basic structure of the descriptive mathematical model we wish to derive from the GSSM at the element level. It is the mathematical model, not the GSSM, which provides the basis for determining probabilities (for standards) associated with system performance requirements, so procedural efficiency is unnecessarily abused by erecting a more complex GSSM than is required by the mathematical model we wish to derive. However, since the mathematical model will be derived directly from the graphic model, the latter must be complete and accurate for the mathematical statement to represent the system faithfully.

D. Mathematical Statement of Functional Relations

Once a system design is defined, a Graphic State Sequence Model of it can be constructed to a desired level of specificity. If we assume the system functions to be completely described, i.e., all personnel and equipment operations defined for every meaningful contingency, we should be able to analyze the relations between the probabilities of the output states of all the PEF Units in the GSSM, and we should be able to derive from those relations a single system-descriptive statement, or Mathematical State Sequence Model (MSSM).

For an understanding of the state sequence analytical procedure, it is necessary that the system be observed from a special, impersonal vantage point from which the defined states indeed are perceived as the states we talk about, and not any others. If a required output state reads, "the three wing nuts in positions x, y and z are tightened so that at least 25 inch-lbs torque would be required to tighten them further," and if only two wing nuts reach that criterion, the the output state is not reached. If the operator says the criterion is reached but it isn't, his saying so is not the system's fault or concern; the system has failed. Only, for the latter condition, the failure is not included in the probability statement for an output state, when a given input state begins the PEF Unit. Assume we know that 20 percent of the men who have performed this unit fail to screw the wing nuts adequately, but they act as if the criterion is met. From the system performance point of view, the output state exists but with a probability of .80 times the probability of the output state due to other factors.

Figure 3 shows a simple PEF Unit with a binary output state, either B or everything else, i.e., $\overline{B}$ = not B. System performance depends upon the occurrence of the output B. In the example, B is said to exist if the system acts as if the three wing nuts satisfied the tightening conditions, and from our hypothetical observations, the system correctly interprets that B exists 80 percent of the time. If the system erroneously operates



$P(B) + P(\overline{B}) = 1.0$

Figure 3. The simplest GSSM of a single PEF Unit.[1]

under the assumption of $\overline{B}$ (that is, if B actually exists, but it is not treated as such), that does not change anything. The system will still not function properly because $\overline{B}$ is interpreted as having occurred.

In the development of the mathematical modeling technique it was recognized that since either $\overline{B}$ or B must occur, the output states in the graphic and mathematical models could omit the $\overline{B}$ (and all analogous output states) without loss of information. Thus, although no further reference will be made to the undesirable output states, they are always understood to exist.

We may now consider the Mathematical State Sequence Model (MSSM) of the graphic representation of a single PEF Unit, such as the one illustrated in Figure 3. Probability theory tells us that

$$P(B \cdot A) = P(B/A)P(A) = P(A/B)P(B)$$

where $P(B \cdot A)$ is the probability of the joint occurrence of B and A, and $P(B/A)$ is the conditional probability that B occurs given that A exists. Similarly $P(A/B)$ describes the degree to which A occurs given that B exists. But if B exists, A must have occurred -- from the system's point of view -- because B results from A. We must assume, initially at least, that the system has been designed to arrive at its specified output state via particular definable procedures, so if state B exists, state A must have existed at the beginning of the PEF Unit, else the PEF Unit would not have occurred.

In reality, it is conceivable that within the generalized system context, state B might seem to occur without prior A. But, the system would then perceive: (1) that its design failed to consider all possible alternatives of A, (2) that $B = A$ or some prior failure condition, or (3) that occurrence of B is a fortuitous, transient condition which is part of, but not relevant to, the ongoing operations.

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[1] GSSM symbols are defined in Figure 2.

Thus, from the system point of view, $P(A/B) = 1.0$, so that $P(B) = P(B/A)P(A)$, and since A represents the output state (or a portion) of a prior PEF Unit, $P(A)$ may be derived in a similar manner. The procedure can be repeated back to the initial input state of the system.

In man-machine systems, certain forms of $P(B/A)$ are often observed to be partitioned. For example, (still referring to Figure 3) assume that A = "power is supplied to VTVM and ON/OFF switch has been ON position for five minutes or more",[1] and B = "VTVM indicator needle reads zero volts." The PEF Unit is, therefore, a simple calibration procedure.

The system requirement states that the needle reads zero volts when no voltage measurement is taken; how one gets there is of no concern to the system. To illustrate a possible complication implied by some PEF Units, assume that we observe many operators using the VTVM under the conditions of this system (or a similar one). We might find, for example that:

1. Given the input state, A, 0.60 of the men actually do calibrate the VTVM, while 0.40 do not. [$K_1 = 0.60$; $K_2 = 0.40$]
2. 0.50 of the time, the VTVM is accurately calibrated, i.e., B already exists without any adjustment required. [$P(B/A_2) = 0.50$]
3. 0.95 of the time when the adjustment is made, the operator achieves the output criterion. [$P(B/A_1) = 0.95$]

The hypothetical observations imply that the system required output state may exist (50 percent of the time) without an operator's doing anything. Since Figure 3 does not allow for that possibility, it is incomplete; instead, the correct GSSM would appear as shown in Figure 4.

The symbols (A_1) and (A_2) designate the alternative means by which state B may be reached. $P(B/A_2)$ is interpreted as follows: given that power is supplied to the VTVM and the ON/OFF switch has been in the ON position for five minutes or more, $P(B/A_2)$ is the probability that the VTVM is accurately calibrated. Thus, state A_2 is state A. The same is true for state A_1.

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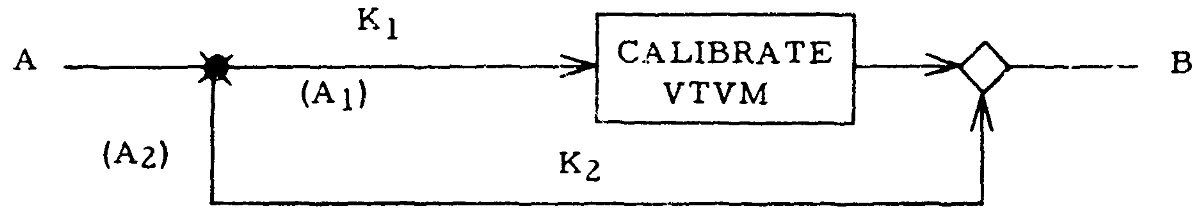
[1] Omitted, for the sake of brevity, are such requirements as "electrodes are in contact only with free air and selector switch is in ____" (a particular voltage position).



$K_1 + K_2 = 1.0$ (These are the proportions respectively established for alternative procedures to arrive at state B.)

$P(B)=K_1P(B/A_1)P(A_1) + K_2P(B/A_2)P(A_2)$ (The different conditional probabilities reflect the effects of the different procedures.)

Note: The subscripts differentiate between the mutually exclusive means of getting from state A to state B; so that, state A ≡ state A_1 ≡ state A_2 or alternatively, $P(A) \equiv P(A_1) \equiv P(A_2)$.

Therefore:

$$P(B) = [K_1P(B/A_1) + K_2P(B/A_2)]\ P(A)$$

Figure 4. GSSM and MSSM of a PEF Unit with the alternative condition that it is not executed.[1]

The MSSM of Figure 4 can be solved using the observed data we hypothesized in the example above:

$$P(B) = [K_1P(B/A_1) + K_2P(B/A_2)]\ P(A)$$

$$P(B) = [.60\,(.96) + .40\,(.50)]\,P(A) = [.54 + .20]\,P(A)$$

$$P(B) = 0.74\ P(A)$$

If, now, the system effectiveness requirement tolerances lead to the conclusion that the VTVM must be calibrated correctly at least 0.80 P(A) of the time, something must be done to modify the system so as to ensure that it meets that criterion; e.g., we might specify that K_1 be increased through improved operator training.

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[1] GSSM symbols are defined in Figure 2.

When several mutually exclusive choices exist, the resulting MSSM is an extension of the one shown in Figure 4. The general model expressing n such choices of means of changing from state A to state B is

$$P(B) = P(A) \sum_{x=1}^{n} K_x P(B/A_x)$$

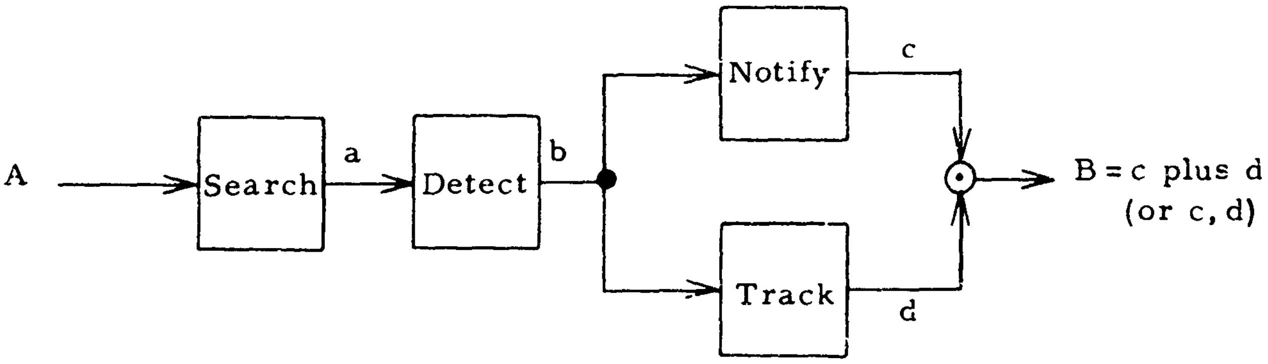
where K_x is the proportion of the time (or of the total number of operations) that B is reached via the alternative symbolized by A_x; if (B/A) occurs at all, then $K_1 + K_2 + \ldots + K_n = 1.0$.

Consider the example of a man determining the probability that he will drive home from work within 30 minutes. If he can (and sometimes does) choose among several routes, he could calculate the relative frequency with which he takes each of them. And he could -- with a large enough sampling -- determine for each route, the probability that he will arrive at home within the time limit. Quite possibly there will be one route which gets him home by 30 minutes more often than any of the others. Clearly, if he does not always take that best route, the probability that he meets his criterion will be less than if he did.

The example illustrates the principle that the probability of an output state decreases with an increase in the number of choices: (1) if the probabilities of the choices differ, and (2) if the relative frequency associated with the selection of a new alternative is split from one with higher relative frequency, and nothing is done to increase the likelihood of selecting a better alternative.

The implications here for system design are apparent: when a high probability of a particular output state is required and an effective and efficient procedure is known to exist, the design must preclude departures from that procedure. The implications for model construction are almost as obvious: the GSSM must include all meaningful possibilities -- even if not explicitly stated in operator instructions -- else the MSSM will yield erroneous results and conclusions.

Inspection of several system designs in GSSM form has led to the finding that the alternative arrangement of PEF Units, described above, is one of two common configurations. The second type may be called "summary," which refers to arrangements of required PEF Units for which no alternative exists. Figure 5 illustrates two ways in which the summary configuration may appear: series (A to a to b) and parallel (b to c and b to d).



$$P(B) = P(c, d/b)\ P(b)$$

$$P(B) = P(c/b)\ P(d/b)\ P(b)$$

$$P(b) = P(b/a)\ P(a)$$

$$P(a) = P(a/A)\ P(A)$$

Therefore,

$$P(B) = P(A)\ P(a/A)\ P(b/a)\ P(c/b)\ P(d/b)$$

Figure 5. Summary configurations -- required series and parallel PEF Units.

The resulting MSSM for the summary configuration is a product of all conditional probabilities. Stated in general form for n PEF Units

$$P(B) = P(A) \prod_{\alpha = 1}^{n} P(O_\alpha / I_\alpha)$$

where O_α is the output state of the αth PEF Unit and I_α is its input state.

The MSSM for the AN/SKQ-1 receive and record activities, shown in Figure 2, combines the alternative and summary configurations. In that figure, (1) if K_{c1} and K_{g2} were omitted, (2) if we let x represent the state, $\Delta t < 20$ sec. and y represent "command to start recording," and (3) if P(A) is used to represent the conditional probability of the output state of A given its input state, then without alternative conditions the GSSM would be purely summary in form, and the MSSM would be

$$P(\text{output state}) = P(x)\ P(y) \prod_{\alpha = A}^{J} (\alpha)$$

When, however, the two alternative situations are included, the MSSM is

$$P(\text{output state}) = P(x)P(y)P(A)P(B)P(E)P(F)P(H)P(I)P(J)\,[K_{c1}P(C) + K_{c2}P(\overline{C})\,]\,[K_{g1}P(G) + K_{g2}P(\overline{G})\,]$$

where $P(\overline{C})$ and $P(\overline{G})$ represent the probability of the existence of the output state without the occurrence of C and G, respectively. While most mathematical models required for the MSSM are summary and alternative types, one additional, rather infrequently used type has been found for repetitive functions designed to increase the accuracy of an output state. An example of this condition is shown in Figure 6.

Consider, for example, the requirement that an estimate of the size of a distant, moving object be made within a specified tolerance with a given probability of accomplishment. If it can be assumed that with each repetition -- performed so as to improve over each preceding estimate -- the probability of estimating within the tolerance level increases by a constant proportion, k, then the mode could be expressed as follows:

> Assuming an exponentially decreasing effect of repetition (because the probability of success cannot be greater than unity), then
>
> $$P(B)_m = 1 - Ce^{-cm} = 1 - [1 - P(B)]e^{-cm} \qquad m = 1, 2, 3\ldots \qquad (1)$$
>
> where $P(B)_m$ is the output probability after m repetitions and $P(B)$ is the output probability with no repetitions, i.e., $m = 0$. (See Figure 6.)
>
> Where $m = 1$, $P(B)_m = P(B)\ \{1 + k\}$
>
> Therefore, after solving equation (1) for c,
>
> $$P(B)_m = 1 - [1 - P(B)]\exp.\ [m \ln \frac{1 - P(B)\ \{1 + k\}}{1 - P(B)}]$$
>
> which can be simplified to
>
> $$P(B)_m = 1 - [1 - P(B)]^{1-m}[1 - P(B)\ \{1 + k\}]^m \qquad (2)$$

If k is not constant, but rather varies as a function of m, the number of repetitions, then that function would be substituted for k.

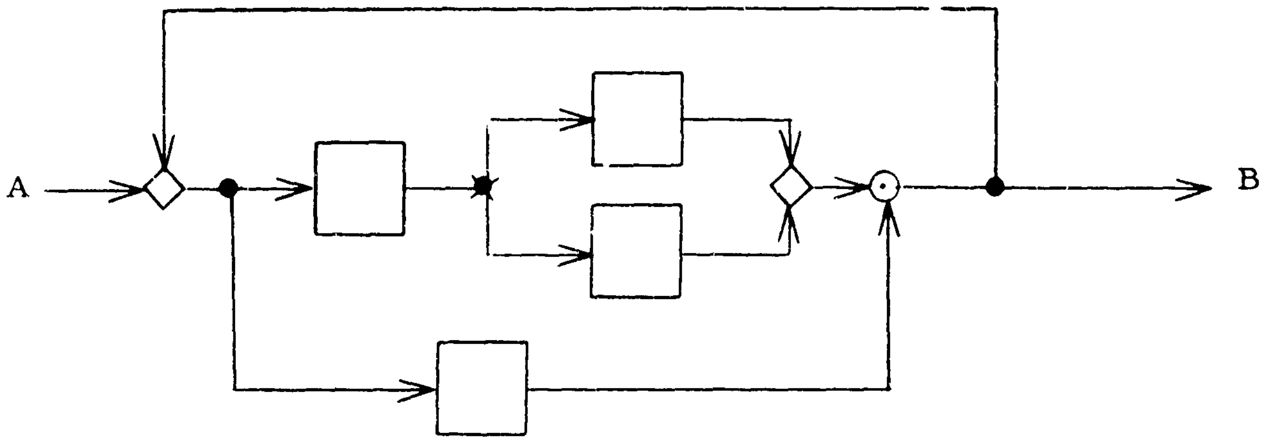


Figure 6. Example of a GSSM for improving an estimate by repetition.

It should be noted that the validity of equation (1) remains to be tested. That can be done by observing how the probability of accomplishing each of a number of relevant tasks changes as a function of the number of repetitions allowed for improving performance of reaching a specified level of excellence.

The three basic mathematical models described above cover all system configurations that have been examined to date. It appears very likely that most, if not all, operations can be described by one or a combination of those three. Once the MSSM for the system has been obtained, it then serves as the foundation upon which allocation is performed.

E. Allocation of Requirements

Allocation is the process of distributing system operational requirements among the system PEF Units. The allocated requirements which appear as components of the output states thus become the standards which must be met in order to achieve the overall system criteria for a successful mission.

1. Problem Definition

Ideally, the data used in the allocation process should be solely restricted to system effectiveness requirements, supplemented when appropriate with hardware design data. However, system requirements may not provide directly for establishment of standards at every level of specificity, particularly at the elemental level. Therefore, to arrive at those standards from system effectiveness requirements, it is necessary (1) to establish a valid distribution rule and (2) to determine the nature of the data to which the rule must apply. The best results would be obtained if those data were reliably measurable and not dependent upon any specific system configuration. However, no objective, independent basis has yet been developed for determining generalizable, consistent human performance measures which are not system-specific. And -- as will be discussed in a later section -- what is available in the form of capability data leaves much to be desired.

Before considering the procedure developed to apply those data in a distribution rule, some initial comments will be made regarding several important considerations in deriving that rule.

Use of mission requirements and system data will most frequently lead directly to establishment of standards for Level I and perhaps Level II PEF Units. Application of the job standards methodology developed to date would provide system related standards for those levels. A requirement remains, however, to develop more detailed standards -- specifically to the element level -- for reasons including the following:

- The absence of standards at lower levels does not permit a test of the "reasonableness" of individual assignments which might suggest reallocation of requirements (when this is possible within the mission context). A test of "reasonableness" here would consist of a gross comparison of assigned requirements and feasible human performance.

- The majority of our tools for measuring or evaluating personnel performance are either insensitive or inefficient at levels much higher than the element level, and job standards at gross levels are difficult to treat. As an example, determining the ability of a person to perform the detection function might entail a complex simulation arrangement, and if substandard performance were noted, a detailed analysis of elemental PEF Units would most likely be required to determine where the deficiencies lie.

- Because personnel functions and tasks vary significantly from system to system, methodological requirements dictate that the "basic building block" of performance be small enough to permit universal identification across systems.

- Transitive use of the method to determine the effect of varying levels of personnel performance as well as use of the method for evaluating occupational structure appears to require that standards be defined at the element level.

Thus, standards associated with all PEF Units will be constrained, if not directly established by system effectiveness requirements. However, the need to allocate to the element level will require the use of data external to the system, and the most obvious alternative is employment of behavioral data of some type. There are several ways in which the allocation may be accomplished, among them the following:

1) Use of an approach which establishes a proportional relation among individual PEF Units using behavioral/systems experts (human factors analysts) or specific systems experts (design engineers or technicians) as judges.

    a) Ranking

        (1) According to specific dimensions (e.g., according to expected errors in performance), or

        (2) According to a general dimension (e.g., an assessment of overall "difficulty" in carrying out the task).

    b) Rating

        (1) Rate individual tasks, elements, etc... according to specific dimensions ...

            (a) Single dimensions

            (b) Multiple dimensions which would require the development of weighting scores.

        (2) Rate individual tasks, elements, etc. according to a general dimension.

2) Use of experimental data from similar or related systems to determine element PEF Unit standard allocations which will satisfy overall effectiveness requirements.

   a) Use directly

   b) Use to establish proportional relations

3) Use of normalized or pooled experimental data found in recently developed "data stores" to determine the proper combination of elemental PEF Unit standards which will satisfy overall effectiveness requirements.

   a) Use directly

   b) Use to establish weighted indices

4) Use of simulation study data obtained through system specific simulation to determine the combination of element PEF Unit standards which will satisfy overall effectiveness requirements.

Each of the approaches above has some merit when evaluated against criteria including:

- Reliability
- Validity
- Accuracy
- Sensitivity
- Objectivity
- Inclusiveness (comprehensiveness)
- Internal Consistency
- Ease of Development
- Ease of Use

The sets of approaches including ranking and those involving scoring by specific system experts, however, have been eliminated due to limitations in reliability and objectivity, respectively. Use of experimental or simulation study data appears to represent a useful approach, but the quality of available data will vary according to the type of system being analyzed; problems of internal consistency may also exist. Use of normalized experimental data and multi-dimensional scoring by behavioral/ systems experts has received greatest attention. That approach is described in some detail in the following section.

2. An Index Development Approach

A scoring method which appears quite promising for use in allocation consists of developing an index for the probability of accomplishing a PEF Unit. It is the goal of this approach to be able to derive a numerical Index of Task Accomplishment (IOTA, or simply I_a) for all man-machine operations based on a function of the variables relevant to effective performance. At the same time, the means by which the IOTA is derived should be as straightforward as possible so as to be obtained reliably by any systems analyst.

The initial task is to define the relevant variables; the following have been identified as at least some of those which may contribute to the Index (with parenthetically indicated, possible scoring categories):

A = the number of human acts[1] in a PEF Unit and for each act (1, 2, . . . , m)

C = continuity (i.e., discrete or continuous)

H = human factors, man-machine interface design (e.g., best possible, acceptable, or poor design)

T = training required beyond high school graduation (e.g., detailed instruction and supervised practice, simple display or verbal instruction, no training)

P = practice or current skill (e.g., recent practice necessary, some practice at any time, no practice necessary)

D = level of discrimination (e.g., personnel activity based on more than one system feature change or activity based on only one system feature change)

R = repetitiveness (e.g., much repetition, some repetition, no repetition)

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[1] An "act" will be defined more fully as the method is developed. For the present, consider the examples "observe . . .", "adjust. . ." and "switch to . . ."

While the list may not be complete, it indicates the kinds of general variables which may enter into index determination.

It will be noted that most of the factors can vary on a continuous scale; however, in order to maximize reliability among indices obtained by different analysts, each continuum is divided into two or three large segments (dichotomized or trichotomized). By accompanying each segment with several examples, a high level of agreement may be expected between scores on the resulting, overall IOTA. That is, since the measures are gross, isolated differences between scores on a particular variable will have a relatively small effect on the overall IOTA because many such gross values are included in index determination.

Once the analyst (or scorer) has assigned a value to every PEF Unit on each variable, the overall I_a must be calculated by inserting the obtained values in an equation describing the relation among the variables. If, for example, the seven listed above are the primary relevant variables,

$$I_a = f(A, C, H, T, P, D, R)$$

The function, itself, must be determined. To find the nature of the function and the constants within the function requires that applicable, experimentally derived objective data be available.

If the assumption holds that the IOTA can be applied to all personnel/equipment functional interactions, then behavioral data stores of the type developed by Payne and Altman offer the required data.[1] While there are certain limitations to the direct use of data for allocating requirements for a specific system, as indicated in the following section, the pooled data characteristic can be used advantageously to determine the function defining the IOTA. To illustrate the approach, assume that a linear relation exists between the IOTA and the variables relevant to effective performance:

$$I_a = K_1 + K_2A + K_3C + K_4H + K_5T + K_6P + K_7D + K_8R$$

A large sample of representative PEF Units would be defined and scored, and a corresponding estimate of I_a (i.e., error probability) for each PEF Unit would be obtained from the data store. Multiple linear

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[1] Payne D., and Altman, J. W. <u>An Index of Electronic Equipment Operability: Data Store.</u> Pittsburgh, Pennsylvania: American Institute for Research Report C-43-1/62-FR, January 1962.

regression analysis could then be used to determine values for the various K's. Forms of the IOTA, other than linear could also be tested to determine the best form of the expression. Utilizing existing computer programs, a large number of forms could be tested quickly and economically.

Given the functional relation, an IOTA for each PEF Unit of a particular system can be calculated. The next problem is to convert I_a values into system-specific probability of accomplishment values such that the probabilities relate to system effectiveness criteria in accordance with their individual contributions to the system. Since the MSSM defines that relation, the model must be satisfied by some probability function of the I_a values. To accomplish that, the following tentative assumptions are made for exploratory purposes:

1) The I_a values lie on an interval scale of measurement.

2) The I_a values can be constrained to lie between zero and 1.0.

3) The transformation from the IOTA to a probability of accomplishment must reflect the relation that the magnitude of the increment in human capability necessary to change the probability of accomplishment increases as the probability of accomplishment approaches 1.0.

The second assumption makes it possible to allocate probabilities of accomplishment by treating the differences between those probabilities and their associated indices according to an established principle for evaluating increments in human performance. Since the IOTA still needs to be developed, it might reasonably be expected to satisfy the second assumption directly by using it as one of the criteria in the developmental process.

The third assumption suggests the hypothetical transformation relation shown in equation (3).

$$\frac{(1.0 - I_a) - (1.0 - P)}{1.0 - I_a} = \frac{P - I_a}{1.0 - I_a} = k \qquad (3)$$

where:

P = the probability component of a performance standard (probability of accomplishment); the P for each PEF Unit is derived from its associated I_a value. Note that P is a shorthand notation for the conditional probability previously referred to as $P(O_\alpha / I_\alpha)$.

k = a constant

Solving equation (3) for P,

$$P = k(1 - I_a) + I_a \tag{4}$$

To satisfy any system-required probability, P_o, involving n PEF Units,

$$P_o = f(P_1, P_2, \ldots, P_n) = f(k, I_{a1}, I_{a2}, \ldots, I_{an}) \tag{5}$$

where the function, f, is determined by the related MSSM. For example, if the MSSM is

$$P_o = \prod_{\alpha=1}^{3} P_\alpha$$

then,

$$P_o = [k(1 - I_{a1}) + I_{a1}][k(1 - I_{a2}) + I_{a2}][k(1 - I_{a3}) + I_{a3}] \tag{6}$$

After solving equation (6) for k, each P_α can be found by equation (4). Those P_α values, then, are the required probabilities of success for each PEF Unit in order for the system to meet its effectiveness criterion.

3. Interim Allocation Technique

In order to provide an interim allocation technique that would fulfill the needs of a basic capability for standards derivation, the use of normalized or pooled experimental data to establish relative weightings among elemental PEF Units was selected as a means for defining IOIA (see approach 3b noted previously).

In our review of related research, the most comprehensive set of behavioral data found was the "data store" developed by Payne and Altman.[1] The purpose of their study was to provide a procedure for the quantitative evaluation of electronic equipment operability. Experimental

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[1] Payne and Altman, op. cit. 1962.

information pertaining to measurable performance in the operation of electronic equipment was abstracted from the literature and organized into a data store containing time and reliability (i.e., probability of successful accomplishment) data. It is intended that the data to be used to score electronic equipment along time and reliability dimensions to determine its acceptability or to determine redesign alternatives which would increase its acceptability.

The major limitations in using the "data store" pertain to task taxonomic structure, reliability, consistency and comprehensiveness Concerning task taxonomic structure, a significant difference was noted between the one found most appropriate in job standards derivation methods and the one employed in the "data store." Specifically, the elemental PEF Unit has been rigorously defined through the use of the Graphic State Sequence Model, whereas the entries in the "data store" include fractionation to "partial elements" which necessitated a translation of "data store" terminology to conform with that of the standards derivation method, and vice-versa. While the translation was made, a certain amount of descriptive precision was necessarily lost. The necessity for translation, of course, introduces a possible source of user error. No statistical reliability index was computed in the present study; however, in a trial application of the data store carried out by Payne and Altman, a range of agreement among raters from 64 to 89 percent was observed.

Problems of consistency and comprehensiveness are attributable to the shortage of well-documented behavioral data in the research literature. Consistency is absent in the conditions under which the behavioral data were collected, size of the sample of observations available to compute time and reliability statistics, constraints placed on performance, and the criteria employed.

Lack of comprehensiveness refers to the extent to which the "data store" omits important elements of personnel/equipment behavior. To improve comprehensiveness is a two-fold task: first, a more careful review of the existing research literature is needed to meet immediate requirements, and second, increased emphasis must be placed on focusing upon a basic framework (e.g., PEF Unit description principles) in collection of behavioral data in the future. The latter task is an extensive but important one, if a meaningful and complete set of data is to be established.

Although the "data store" has certain significant limitations with respect to its use in allocation, reliability data from the store were used as indices of task accomplishment in trial application of the method to the AN/SPS-40. Its use was predicated for the most part on the fact that it constitutes the most complete set of behavioral data classified according to tasks normally encountered in weapon system operation and maintenance. However, due to some of the limitations noted caution must be employed in use of "data store" information. In the AN/SPS-40 application, the reliabilities were not taken at their absolute values, but rather were used to scale the various PEF Units. In other words, the "data store" reliability figures were treated as though they were a fully developed set of Indices of Task Accomplishment. Therefore, since the values are used principally to determine PEF Unit combinational weights, it is not necessary to make any assumptions regarding the accuracy of the reliability values themselves.

In summary, it was found that at least one set of data could be used successfully to establish Indices of Task Accomplishment and allocate standards; however, due to limitations noted, future applications of "data store" indices must be made carefully and tentatively. The approach for arriving at a more reliable and comprehensive basis for allocation has been described above. To provide an objective means of allocation applicable to a wide spectrum of man-machine systems, effort should be directed toward developing the approach as well as toward close examination of the limitations of existing data stores.

F. Integrative Use of the Method

In Section I-A, it was noted that the method must provide a means for estimating the way system operation would be affected by deviations from established personnel performance standards. This section explores the integrative use of the method for that purpose.

Once standards have been allocated to system PEF Units, the question arises as to how well those standards can be met. Two primary concerns are (a) interpreting results, and (b) obtaining indications of what to do about discrepancies. Since the fundamental goal of the technique is to aid in the development of the most effective, feasible system to accomplish the requirements of the mission assigned, it is necessary to find the optimal match between personnel performance levels required by a particular system design (standards) and the performance levels that can be expected from personnel being considered for assignment to that system.

For the method to be employed for that purpose, some form of personnel capability or expectancy data are required, i.e., S_c input data for the integrative model included in the conceptual framework (see Section II-B). At present, unfortunately, no comprehensive and fully reliable store of human performance capability data is available. In the absence of behavioral data store expectancies, however, capability data can be obtained on the specific personnel group being considered for assignment to the system by measuring the performance of that group on the PEF Units resulting from the standards derivation process. Another source would be proximate data obtained from previous studies of personnel operations that are comparable to those required by the system under analysis. A less adequate alternative is to use the "data store" developed by Payne and Altman.[1] That alternative was selected in the present study since the "data store" constitutes the only available source of personnel capability data.

The use of the method as a means for relating system requirements (standards) and real world potentialities is described below.

1. Illustrative Case

To illustrate the use of the integrative procedure, three hypothetical sets of probabilities have been generated and are presented in Table 1. Each set is to be interpreted as applying to a system represented by three functions (F_1, F_2 and F_3) such that F_1 is composed of three elements, and both F_2 and F_3 comprise four elements each. The three sets of values are totally independent and may be imagined to apply to three different systems, or as three mutually exclusive hypothetical possibilities for a single system. In any event, the non-parenthetical numbers represent the probabilities with which humans can be expected to perform the associated PEF Units, i.e., reliable human capability values. The numbers in parentheses are derived, allocated probabilities, weighted on the associated hypothetical expectancy values; those numbers represent required performance levels.

It is assumed that the MSSM for each Function is a simple multiplicative model; thus, the product of the capability values for the elements in any one row in Table 1 is equal to the number under S_c in that row. Similarly, the product of the associated parenthetical, allocated values in a single row equals S_r, the operational requirement. In most of the subsequent discussion, we will be interested in comparing system operational requirements (S_r values) with the derived capability scores (S_c values) as well as in comparing the allocated and capability values at the element level. The kinds of considerations and operations for the comparisons at the two levels are quite similar.

The three sets of hypothetical data (non-parenthetical values) were generated so that (1) in Set I, the S_r values exceed S_c values;

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[1] Payne and Altman, op. cit., 1962

(2) in Set II, all capability scores are larger than the corresponding required values; and (3) in Set III there is one high S_c probability and two S_c values that are below S_r, but the system values are about the same. It may be noted that the probabilities of accomplishing system output states are obtained by multiplying the three values directly above each of them; for example, in Set I,

System $S_r = [.940]\,[.939]\,[.951] = .839$ and

System $S_c = [.854]\,[.919]\,[.907] = .712$

2. Interpretation

Discrepancies between corresponding S_c and S_r values -- for any set of data -- may result from one or more of the following conditions:

a. Human capabilities differ from those required, and changes in skill levels or number of personnel are indicated through modifications in training or selection procedures.

b. One or more components of the System Effectiveness Requirement (SER) at one or more levels of specificity is incompatible with that which can be achieved for the system design used in the analysis.

   . A different system design could meet the requirements.

   . The criteria used for setting the SER do not correspond to that dictated by system context.

c. The SER, in combination with decision criteria, is set unrealistically high for any conceivable system design (or too low for the system to be useful).

d. Decision criteria used in the allocation process are unnecessarily stringent or does not correspond to actual system context requirements.

e. The system may not be appropriately modelled, either graphically, mathematically, or both.

For example, Set I might represent a system whose design may need to be modified. Excluding for the moment the possibility of other bases for the discrepancies between S_r and S_c, each Function would need

Table 1

Three Hypothetical Sets of Performance Standards and Corresponding Capability Levels with the System Operational Requirements that Must be Met

Data Set	Function	Element				Capability S_c	Required S_r
		1	2	3	4		
I	F_1	(.993)	(.988)	(.958)[1]	----		.940
		.983	.971	.895[2]	----	.854	
	F_2	(.984)	(.987)	(.979)	(.988)		.939
		.978	.983	.970	.986	.919	
	F_3	(.990)	(.988)	(.989)	(.983)		.951
		.982	.978	.980	.964	.907	
				System		.712	.839
II	F_1	(.957)	(.988)	(.994)	----		.940
		.965	.990	.995	----	.951	
	F_2	(.983)	(.973)	(.991)	(.991)		.939
		.998	.997	.999	.999	.993	
	F_3	(.993)	(.996)	(.985)	(.976)		.951
		.997	.998	.994	.991	.980	
				System		.925	.839
III	F_1	(.965)	(.986)	(.988)	----		.940
		.944	.976	.981	----	.904	
	F_2	(.992)	(.983)	(.971)	(.992)		.939
		.999	.998	.997	.999	.993	
	F_3	(.992)	(.981)	(.990)	(.987)		.951
		.991	.975	.986	.982	936	
				System		.840	.839

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[1] Parenthetical numbers are derived, allocated probabilities; e.g., note that (.993) (.988) (.958) = .940 = S_r for F_1 of Set I.

[2] Expected probabilities of personnel performance obtained from capability data.

to be redesigned. That does not mean that the probability of accomplishing each element within a given function must be increased as a result of the redesign; it is conceivable that in producing a large increase in the probabilities of accomplishing some elements, others may be forced down slightly. For example, the probability associated with Element 4 in F_2 might tolerate a reduction of .001 or .002 in order to increase the probabilities for accomplishing the other three elements.

Similarly, time allowances (where critical) and tolerances, or other output state measures, may need to be altered by redesign so that probabilities of accomplishment are increased. As long as the system effectiveness specifications do not state requirements at the element level, reconstruction of the design at that level theoretically can assume any form. Of course, redesign must always take into consideration such additionally specified decision criteria as personnel training requirements and cost.

It is also conceivable that the original requirement of .839 is higher than needed in the system context. All other things being equal, if the system could actually serve its purpose by supplying a specified output with a probability of .700 ($S_r = .700$), then the values in Set I are satisfactory ($S_c = .712$).

Almost any effectiveness requirement which is possible could be met if cost and time to realize the design were unlimited. However, restrictions on economy of all kinds normally set limits on what may reasonably be expected from a system. Considering the immense number of permutations and combinations of elements in a system, it is not a simple matter to specify a general procedure for determining the non-feasibility of achieving system requirements. The decision may have to rest in the hands of the responsible system designers who are unable to find alternative means of providing the required system output state. As a result, either the effectiveness requirements, the decision criteria, or both may need to be relaxed somewhat.

Just the reverse may be true for the system represented by the data in Set II of Table 1, where S_r is less than S_c. That condition could arise if the effectiveness requirement and/or decision criteria are more relaxed than the system mission actually requires. On the other hand, it may well be true that the system mission can in fact be accomplished successfully at the originally stated requirement level; $S_c > S_r$ might then be the result of overdesign. An overdesign indicated by a large discrepancy between S_c and S_r generally corresponds to an expenditure of hardware or personnel (number or capabilities) greater than necessary, i.e., excess costs in general. Note, however, that it may be possible to trace overdesign to particular elements. For example, in F_1 of Set II, only Element 1 may be overdesigned while Elements 2 and 3 appear to have very similar allocated and capability probability values. Similarly, the associated values in Element 2 of F_3 are almost identical.

When applying the technique to an existing system, it is in the best economic interests to investigate all possible sources of a difference between S_c and S_r before deciding upon a course of action. One source which has not been mentioned so far could lie not in the system, but in the basis of the decision that a discrepancy exists. That is, the system may not have been modeled accurately, so that an erroneous conclusion is drawn. It is likely that such errors will occur less and less frequently as experience is gained with the use of the technique. However, in the initial phases of its application, some means for double-checking the accuracy of the models may be necessary.

Considering Set III in Table 1, it is evident that if no S_r values were specified at the Function level, the overall system effectiveness requirement of .839 could be met as indicated by the results of integrative analysis (.840). However, Function requirements are indicated, and for two of the Functions (F_1 and F_3) the capability scores indicate inability to meet those requirements. That inability is particularly reflected in Elements 1 and 2 of F_1 and Elements 2, 3, and 4 of F_3. On the other hand, the ability to perform F_2 is much greater than specifications demand.

Conclusions and possible actions resulting from these findings are approached in the same way as has been discussed above where, for the entire system, all S_c values were higher or lower than S_r values. However, when some are higher and some are lower, it is less likely that the source of the discrepancies lies in erroneous modeling, unless there is some reason to suspect that the analyst is differentially treating some Functions with greater care or accuracy than others. Also, where the Function specifications are not all met, but system effectiveness requirements are, the added alternative exists to re-evaluate the basis for establishing requirements at the Function level. It may be less costly and serve the mission purpose to accept the overall system as it stands, rather than to seek a means of revising Elemental PEF Units to meet the standards at the Function level.

G. Overview of Procedure

The output of the method development effort described in the preceding sections, in conjunction with method application on the AN/SPS-40, resulted in a procedure for applying the method to establish performance standards. Detailed step-by-step procedures are presented in Appendix B. A brief overview of the procedure in graphic model form is shown in Figure 7 and is summarized below by procedural steps.

1. Collect Input Data

Obtain system operational requirements data, system descriptive data, design goals and data concerning functions performed, equipments involved and so on. Data sources will vary depending on whether the system already exists or is in the conceptual or design state. If the system is an existing one, sources of data should be system development and test reports, operation and maintenance guides and procedures, personnel/equipment analysis data and on site observations. If the system is in the design stage, sources might be system planning and research reports, Tentative Specific Operational Requirements (TSOR), Proposed Technical Approaches (PTA's), Specific Operational Requirements (SOR), Technical Development Plans (TDP's) and interviews with cognizant design personnel. (Data collection may be continued until the GSSM is completed.)

2. Define System Input and Output States

Organize the data and define all relevant features of the input and output states of the total system as precisely as possible. All constraints or assumptions about the general state of the system, as for example, state of alert, should also be specified in this step.

3. Define System Functions

On the basis of the data collected and the input-output states, define the general Functions mediating the input and output states of the system.

4. Prepare Graphic Model Data Form (GMDF)

Prepare detailed GMDF's for each Function detailed, one for each level of specificity. The GMDF should include complete specificati of all meaningful input and output states for every PEF Unit.

5. Construct Graphic State Sequence Model (GSSM)

Based on the GMDF's and the GSSM construction guidelines, develop state sequence models for each relevant level of each function and illustrate graphically the relations among all PEF Units with all possible meaningful input and output states.

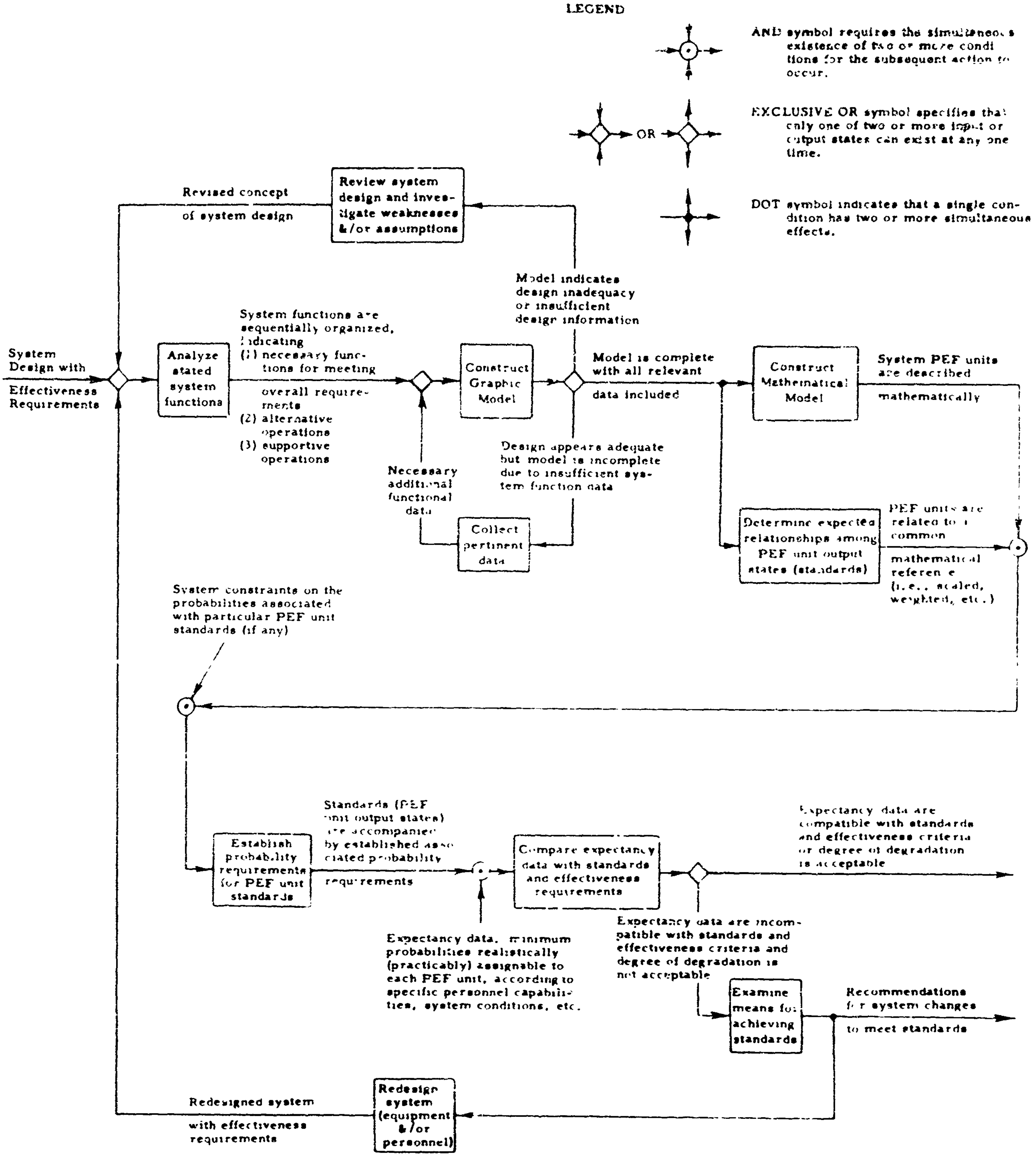


Figure 7. Graphic model for establishing system-related job standards.

6. Construct Mathematic State Sequence Model (MSSM)

From the GSSM configuration and the principles of probability theory, specify the probability of achieving the system output state as a function of the probabilities of accomplishing the personnel equipment functions within the particular system context.

7. Allocate Requirements to PEF Units

Determine the independently derived Index of Task Accomplishment (I_a) for each PEF Unit. From the probability function of the I_a value and the MSSM, compute the probabilities of success of the PEF Unit output states (standards) necessary for total system requirements to be met. Repeat the allocation determination for extreme alternatives, and determine the possible range of PEF Unit output state probabilities which will satisfy the total system output requirement.

IV. EXTENSION OF BASIC CAPABILITY

In Section I-B (Scope), it was noted that the present study was devoted to developing a basic capability for meeting two methodological objectives. This section considers additional problem dimensions and represents a first step in extending that capability.

A. Integration of Maintenance Considerations

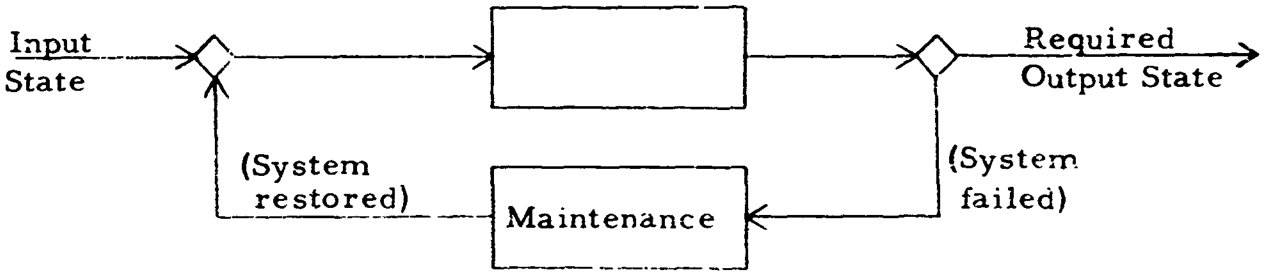
While the description of method development in preceding sections has been oriented toward developing standards for operator performance, the same general procedures and modeling approach are applicable to system maintenance. The basic distinctions are that for maintainer performance: (1) time, rather than probability of success, is the primary standard of performance; and (2) due to the fact that the probability of failure need only be introduced at the most general level of modeling, it is not necessary to include failure and maintenance considerations in the detailed graphic and mathematical state sequence models used to represent operator performance.

Overall corrective maintenance requirements are derived from availability or dependability requirements established for the system or subsystem. Availability, A, or the expected probability that the system will be operating at a specified point in time can be expressed:

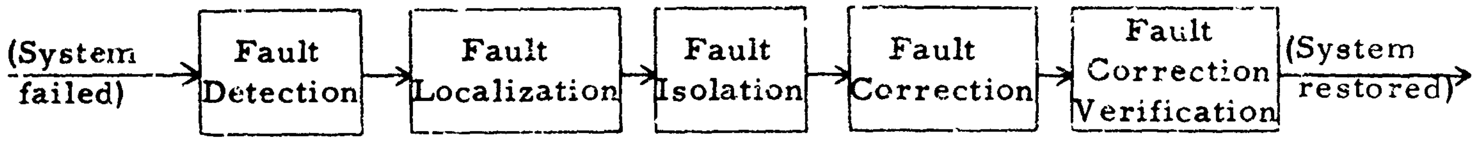
$$A = MTBF/(MTBF + MTTR),$$

where MTBF is Mean Time Between Failure and MTTR is Mean Time To Restore the system or equipment to operation in the event of failure. MTTR thus constitutes the most general standard for maintenance performance.

Since a system failure potentially constitutes the output state of any personnel/equipment functional unit, the occurrence of a maintenance task can be incorporated in the system state sequence model as illustrated below:



The maintenance task can, in turn, be modeled in more detail as shown:



The probability of successfully completing the maintenance task is, by definition, unity. The probabilities of completing the maintenance subtasks illustrated above, however, are not necessarily equal to unity and may therefore affect overall task time (e.g., the replacement of a good part incorrectly identified as being failed increases total task time). Since statistics pertaining to the probability of performing maintenance subtasks are not necessarily required in the development of standards, primary consideration will be given to time parameters of the subtasks.

At the extremes of specificity of standards for the maintenance task are the overall MTTR requirement, and standards to perform each maintenance task which might be required in the system. The latter standards can be determined theoretically using the fixed relation between (1) the failure rates and the required maintenance times for all elements in the system and (2) a basis for time allocation such as an Index of Task Accomplishment. The relation between system MTTR and individual maintenance actions may be expressed as follows:

$$\mathrm{MTTR} = \left(\sum_{i=1}^{n} \lambda_i R_i\right) / \sum_{i=1}^{n} \lambda_i$$

where:

R_i = time to carry out maintenance on the i th element

λ_i = failure rate of the i th element

n = number of possible maintenance actions in the system (equals the number of on-line replacement elements)

Since most systems involve many maintenance tasks which are quite similar, the most appropriate approach appears to be to develop a set of standards which is intermediate in specificity. Depending on the nature of the system being analyzed, and the particular method in which the standards are to be utilized, maintenance time standards could be established for various categories of maintenance tasks. An illustrative classification system would consist of the following:

1. Maintenance tasks involving automatic localization of failed modules.

2. Maintenance tasks involving the use of test equipment to observe simple input-output relations to isolate failed modules and parts.

3. Maintenance tasks involving more complex diagnostic activities than those described in Categories 1 and 2.

The types of data required to develop standards would include the following:

- Identification of the maintenance task for each element[1] (or group of elements maintained in a similar manner) in the system;
- The category of maintenance in terms of human capability requirements; and
- The failure rate of each element (or group of elements maintained in a similar manner).

Carrying out the procedures outlined in MIL-M-23313A for predicting mean time to restore would satisfy the first and third requirements;[2] however, additional characterization of the various maintenance tasks with respect to demands on human capabilities is still required. In the development of standards, failure and maintenance considerations need only be considered at the most gross level; it is not necessary to reproduce those considerations in the detailed graphic or mathematical models. The major task involved in establishing standards, therefore, consists in using the data above plus an Index of Task Accomplishment, similar to that described in Section III-E to allocate standards.

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[1] In this section, element refers to the hardware item on which the maintenance action takes place, i. e., module, piece part, etc.

[2] Maintainability Requirement for Shipboard and Shore Electronic Equipment and Systems, MIL-M-23313A, 9 October 1963.

To illustrate the approach, it is assumed that the combined failure rates of elements maintained according to the three categories described above have been determined:

Maintenance Category	Failure Rate of Elements in the Category (failures per hour)
1	.002
2	.006
3	.002
Total System	.010

Substituting known values in the MTTR relation given above, one obtains:

$$MTTR = 0.2R_1 + 0.6R_2 + 0.2R_3$$

If it is assumed that the Indices of Task Accomplishment (I_{a_i}'s) are 1, 2, and 3 for maintenance categories 1, 2, and 3, respectively, the following relation can be stated:

$$R_1 : R_2 : R_3 = I_{a_1} : I_{a_2} : I_{a_3} = 1 : 2 : 3,$$

and substituting in the MTTR relation, assuming the overall MTTR is 1.0 hour,

$$MTTR = 1.0 = 0.2R_1 + 1.2R_1 + 0.6R_1$$

$$1.0 = 2R_1 ; \qquad R_1 = 0.5 \text{ hours}$$

$$R_2 = 1.0 \text{ hours}$$

$$R_3 = 1.5 \text{ hours}$$

The complete set of standards for system maintenance would then be:

Maintenance Category	Failure Rate (failures per hour)	Time Requirement (hours)
1	.002	0.5
2	.006	1.0
3	.002	1.5
Total System	.010	1.0

More detailed maintenance task classifications could be established for any specific system. The selection of an exact classification system would take into account the variety of maintenance tasks in the system as well as training and occupational hierarchy considerations. Additionally, techniques may be developed for establishing standards for maintenance subtasks.

B. Consideration of Additional Standards Components

Means of determining time and accuracy components of PEF Unit standards are not included in the basic capability represented by the method described in Section III. If those components of performance standards are taken into explicit consideration and not held constant, the allocation procedure becomes increasingly complex since it is not likely that components are independent. The solution of the Mathematical State Sequence Model will yield different results as probability, time and/or accuracy values are varied for one or more PEF Units. Efforts to trade-off time and accuracy or time and probability, for example, will result in simultaneous changes in allocated probability, time, and accuracy requirements throughout the system. Thus, the interdependence of all components must be appropriately reflected by the technique. This section explores various approaches for integrating time and accuracy components with the probability of accomplishment component.

1. Preliminary Considerations and Assumptions

The exact nature of the Index of Task Accomplishment (IOTA) still remains to be specified, although in Section III-E it was suggested that it might be a derived "score" or a value which is a function of several weighted variables. While time and accuracy were not included in the previous discussion, a more complete IOTA function could be described which varies with:

- Man's capability, M,
- Difficulty of the job, J,
- Time allowed, t, and
- Accuracy required (measurement tolerance permitted), L.

If i is defined as the variable IOTA,

$$i = f(M,\ J,\ t,\ L). \tag{1}$$

It is assumed that M and J can be defined as discrete variables,[1] while t and L are continuous such that:

$$\frac{\partial i}{\partial t} \geq 0; \ \frac{\partial i}{\partial L} \geq 0$$

$$i(M + \epsilon,\ J,\ t,\ L) - i(M,\ J,\ t,\ L) > 0$$

$$L(M,\ J + \epsilon,\ t,\ L) - i(M,\ J,\ t,\ L) < 0$$

where ϵ is a small positive increment.

The relation above indicates that i reflects the "ease" with which a man can perform a job, since i increases as (1) more time is allowed, (2) more tolerance is allowed (accuracy requirement relaxed), (3) man's capability increases, and (4) job difficulty is reduced.

In order to treat the time and accuracy components separately, Equation (1) may be rewritten:

$$L = f\{f_1\ (M,\ J),\ f_2(t),\ f_3(L)\} \tag{2}$$

In the subsequent discussion, the probable forms of functions f_2 and f_3 in Equation (2) will be discussed.

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[1] Time and accuracy variables can be treated as discrete; however, such an approach would require the development of a large number of matrices relating time and accuracy for each probability level and for every PEF Unit.

2. An Example Relating the Index of Accomplishment and Time

One basic assumption concerning the time variable is that a maximum value exists for time, beyond which i does not change, if the accuracy requirement is held constant. That value of i is I_a:

$$\lim_{\substack{t \to \infty \\ (L\ \text{constant})}} i = I_a = f\{f_1\ (M,\ J)\ f_2\ (T_{max})\ f_3\ (L)\} = f\{f_1\ (M,\ J)\ f_3\ (L)\} \qquad (3)$$[1]

To aid in the derivation of $f_2(t)$ and the logic behind the above assumption, a hypothetical example will be used. Consider that 100 people of relatively equal capability are asked to perform a certain task as rapidly as possible; the task is a go/no-go type which does not involve an accuracy level. We would expect the results -- number of people versus time to perform the task -- to be normally or lognormally distributed over time.[2]

Of the 100 people. some will not complete the task properly even though they may have thought they did. Let us say that 95 of them succeeded. It will be assumed then, that the times for successful and unsuccessful persons are both distributed in the same way. It will also be assumed that if the same group had all the time they needed to do the same task, the probability of a successful performance would still be .95. This assumption needs to be tested, but reflects the consideration that in spite of the advantage gained by removing the time constraint, we might expect degradation in performance due to other factors. For example, those who customarily work fast might lose interest and become careless if they were not expected to use their speed skills. Also, personnel under observation usually make a conscious effort to display better performance than under normal conditions, so that a distorted picture might be attained unless the people did not know they were being observed. But even if personnel had all the time they needed in an actual operational situation, there is some question as to whether they would respond to temporal freedom constructively. These considerations could serve to cancel out any advantage gained by placing no time limit on task performance.

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[1] It may be noted that Equation (3) defines I_a as it is used in Section III-E and in Appendix B.

[2] See (1) Conrad, R and Hille, B. A. "Comparison of Paced and Unpaced Performance at a Packing Task," *Occup. Psych.*, 1955, *29* 15-28, and (2) Harrison, G., *et al.* Maintainability Prediction: *Theoretical Basis and Practical Approach (Revised)*. Washington, D. C.: ARINC Research Corp. Publication 267-02-6-420, December 1963.

3. A Proposed Time Function

Based on the two assumptions above, it should be possible to plot i vs t assuming, as stated earlier, that the originally computed I_a for a given task is the index of accomplishment when no time limit is imposed. In the example above, that would mean that I_a is associated with the .95 proportion of successful personnel, and i would be expected to be a monotonic function of time, related to the integral of the normal or lognormal distribution.

We will proceed by assuming a task whose observed frequency distribution of accomplishment best fits a Gaussian (normal) curve. Under that assumption, it would be expected that i might closely fit the following function:

$$i = I_a \int_{-\infty}^{t} \frac{1}{\sigma_\tau \sqrt{2\pi}} \left[\exp. - \frac{(\tau - \bar{\tau})^2}{2\sigma_\tau^{\,2}} \right] d\tau \qquad (4)$$

where

τ = the independent variable (time) of the Gaussian distribution fitted to the observed data

$\bar{\tau}$ = the mean time for that distribution

σ_τ = the standard deviation of the distribution

t = integration time

exp. = exponent of e; i.e., (exp. x) $\equiv e^x$

Equation (4) fails to model all aspects of the expected distribution, however, because it has a non-zero value for t=0, and i would be expected to be zero below a minimum positive time, T_{min} (e.g., one would not expect to find anyone who can tune a receiver in a few milliseconds, if it is not already tuned). Additionally, it seems a reasonable assumption that beyond some maximum time, i will remain constant, i.e., beyond T_{max}, $i = I_a$; however, Equation (4) would specify that $T_{max} = \infty$, which is not a useful concept. In an effort to incorporate these practical constraints, a sinusoidal approximation to the normal curve was developed. Subsequently, it was discovered that Raab and Green[1] suggested a similar approximation which is

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[1] Raab, D. H. and Green, E. H. "A Cosine Approximation to the Normal Distribution," Psychometrika, 26, 447-450 (1961).

slightly simpler than the one we derived, so we elected to use theirs; its general form is

$$f(x) = \frac{1}{2\pi}\,(1+\cos x) \qquad \text{for } -\pi \leq x \leq \pi \qquad (5)$$

Utilizing our symbology and assumptions, then, Equation (4) can be approximated:

$$i = I_a \int_{T_{min}}^{t} \frac{1}{2\pi\,\sigma_\tau} \left\{ 1+\cos\left(\frac{\tau - T_{min}}{\sigma_\tau}\right) - \pi \right\} d\tau \qquad \text{for } T_{max} \geq \tau \geq T_{min} \qquad (6)$$

where

$T_{max} - \bar{\tau} = \pi\,\sigma_\tau$ and $T_{min} - \bar{\tau} = -\pi\sigma_\tau$ so that

$T_{max} - T_{min} = 2\,\pi\sigma_\tau$

$$i = I_a \qquad \text{for } \tau \geq T_{max} \qquad (7)$$

$$i = 0 \qquad \text{for } \tau \leq T_{min} \qquad (8)$$

Solving Equation (6), it can be shown that

$$i = I_a \left[\frac{t - T_{min}}{2\pi\,\sigma_\tau} + \frac{1}{2\pi}\,\sin\left(\frac{t - T_{min}}{\sigma_\tau} - \pi\right)\right] \qquad \text{for } T_{max} \geq t \geq T_{min} \qquad (9)$$

Additionally, Equations (7) and (8) still apply when t is substituted for τ.

Referring back to Equations (2) and (3), it may be noted that the bracketed portion of Equation (9) is the proposed $f_2(t)$.

In essence, it appears likely that data obtained from observing task performance will display a normal (or lognormal)[1] distribution of frequency of task accomplishment as a function of time. It is also likely that the means

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[1] If a lognormal distribution is found, i. e., if the distribution is highly skewed toward longer time values, $\log \tau$, $\log T_{max}$ and $\log T_{min}$ must be substituted for τ, T_{max} and T_{min}, respectively, in Equations (6), (7), and (8).

($\bar{T}$) and standard deviations (σ_T) will differ for different tasks, so that the interval represented by $T_{max} - T_{min}$ will vary, depending upon the "complexity" of the task. The data may also show other regular relations, such as a correlation between $\bar{T}$ and σ_T; it would not be unreasonable to expect that, as task "difficulty" increases, both the mean time to accomplish a task and the variability would also increase simultaneously. Whether the relation is definable and reliable remains to be tested.

4. Determining the Index Value for Allocation

If no time limit is specified for a system, the PEF Units' index of accomplishment is its maximum i value, or I_a. When I_a quantities have been calculated for all PEF Units, those maximum indices become the values which are scaled so as to achieve the system effectiveness requirement, F_0, via the MSSM. It is assumed that scaling I_a values, according to the hypothetical monotonic transformation discussed in the allocation section, satisfies the secondary criteria of minimizing cost or training or some combination of factors. Thus, it has also been assumed that the i function depends solely upon I_a and time and that its variation in time does not affect the satisfaction of the secondary criteria.

If a time limit is specified for the system, the effectiveness requirements include T_T, the total allowable time to achieve the output state, as well as P_0, the probability specified for the system output. As a result, all MSSM-related PEF Unit probabilities of accomplishment must be calculated so as to satisfy both requirements. Combining the probability and time functions to solve the MSSM, then, assumes not only that there is a definable function, $f_2(t)$, for every PEF Unit, but also that i values for different PEF Units (1) are comparable (i.e., lie on the same scale) so that the values can be weighted relatively to satisfy P_0 without altering their interrelations, and (2) are independent, so that no error is generated by bringing them together in the MSSM.

To maximize the accomplishment probabilities and simultaneously meet the system effectiveness requirements involves finding the best solution to a series of simultaneous equations. To illustrate the processes, a simple hypothetical example will be used.

Assume a system composed of three PEF Units such that the MSSM is

$$P_0 = \prod_{\alpha=1}^{3} P(O_\alpha / I_\alpha) \qquad (10)$$

where I_α is the input state and O_α is the output state of the αth PEF Unit.

From previous assumptions regarding the monotonic relation between IOTA and the probability of task accomplishment, the following functional relation has been established:

$$P(O_{\alpha}/I_{\alpha}) = f(i_{\alpha}) \tag{11}$$

for all three α. Also, from Equation (9), we can indicate generally that

$$i_{\alpha} = g(t_{\alpha}) \tag{12}$$

where g is a different function from the f in equation (11). This assumes that for each PEF Unit, I_2, T_{min} and α are known.

Substituting in Equation (10), Equation (13) results for a specified P_o.

$$P_o = \prod_{\alpha=1}^{3} f\{g(t_{\alpha})\} \tag{13}$$

Equation (13) is constrained by the requirement that

$$\sum_{\alpha=1}^{3} t_{\alpha} \leq T_T \tag{14}$$

It is possible that there is more than one solution to Equation (13), even under the constraint of Equation (14), since $f(i_{\alpha})$ involves an unknown constant, k. However, additional analysis is required to establish the appropriate criterion for specifying the unique solution. Suffice it here to say that one may reasonably expect the time component of the standard to be determinable mathematically, if the basic assumptions -- which have been verbalized throughout this section -- are tenable.

5. Determining the Accuracy Component of the Standard

In a similar way, f_3 -- the function of the accuracy component of the standard -- in Equation (2) may be estimated. This amounts to determining the effects of various accuracy requirements associated with output state measures. Assuming time to be held constant, it appears likely that if many people were given the task to measure a parameter, the results would be expected to be distributed normally about the true measure of that parameter. Therefore, using Equation (5) as the approximation to the Gaussian curve, the measurement function, f(m), would be

$$f(m) = \frac{1}{2\pi\sigma_m}\left(1-\cos\frac{m-\bar{m}}{\sigma_m}\right) \qquad \text{for } -\pi \leq \frac{m-\bar{m}}{\sigma_m} \leq \pi \qquad (15)$$

where $\bar{m}$ is the true measure and σ_m is the standard deviation of the distributed measures, m. Since, however, we are only interested in determining measurability <u>within a tolerance</u>, say ±L, then the distribution can be looked upon as an error curve with $\bar{m} = 0$. Therefore, Equation (15) can be rewritten

$$f(m') = \frac{1}{2\pi\sigma_m}\left(1-\cos\frac{m'}{\sigma_m}\right) \qquad \text{for } -\pi \leq \frac{m'}{\sigma_m} \leq \pi \qquad (16)$$

where $m' = m-\bar{m}$

To determine the probability of measuring within ± L, Equation (15) is integrated from zero to L and multiplied by two, because the tolerance encompasses the center of the Gaussian distribution symmetrically. Thus, that probability is approximated by

$$P(L) = \int_0^L \frac{1}{\pi\sigma_m}\left(1+\cos\frac{m'}{\sigma_m}\right) dm'$$

$$P(L) = \frac{1}{\pi}\left(\frac{L}{\sigma_m} + \sin\frac{L}{\sigma_m}\right) \qquad L \leq \pi\sigma_m \qquad (17)$$

Equation (17) seems to correspond to what might logically be expected, viz., (1) the probability of measuring a value increases as the allowable tolerance increases and (2) the probability decreases as the variance of the measures increases. However, if Equation (17) does reliably represent the actual relation, it still remains necessary to determine or estimate σ_m. This may be accomplished by collecting controlled observational data or by obtaining judgments of P(L), given selected values of L, by a number of knowledgeable judges. It is possible that a discrete number of practicable estimates of σ_m can be found for specific classes of performance, so that P(L) would be a continuous function of L for a given task within a particular known classification.

In the derivation of Equation (9), a constant value of I_a was assumed. As a result, it is evident from Equation (3) that that was tantamount to assuming constant values for M, J, and L. To vary L means, then, that I_a in Equation (9) must be replaced by its equivalent $f_1(M, J)\ f_3(L)$. As before, M and J are still constant, since the discussion concerns a particular set of human capabilities operating on a particular job. Therefore, from Equation (17) it seems reasonable to define $f_3(L) = P(L)$.

To conclude, therefore, it is not much of a problem to hypothesize f_2 and f_3 of Equation (2), but it seems evident, from the discussion throughout this section, that the real problem now lies in obtaining sufficient pertinent, accurate and internally consistent data to support or refute the expected relations which have been hypothesized here.

V. METHOD APPLICATION

The job standards derivation method was applied to an operational Navy shipboard subsystem for the purpose of testing and refining the various techniques and procedures being developed. By testing the method empirically during its development using actual system data, there is added assurance that the method possesses sensitivity and practical utility necessary for its use by the Navy as a general system analysis tool.

Only a brief discussion of method application is presented here due to the classified nature of the AN/SPS-40 system data analyzed. The numerical standards established for the various AN/SPS-40 PEF Units are presented in Volume II, together with all graphic and mathematical state sequence models and an appraisal of many of the detailed aspects of the method application to the AN/SPS-40.

A. Selection of Test Subsystem

Selection of a test subsystem was based on a comparison of the relative merits of several AAW and ASW subsystems. The selection process proceeded according to the following steps:

- Development of selection criteria;
- Identification of AAW and ASW subsystems;
- Data collection from Navy fleet and training facilities;
- Relative evaluation of subsystems based on selection criteria; and
- Joint conference with contract monitor to select the final test subsystem.

Selection criteria were developed according to two major guidelines: (1) the tryout subsystem must have the characteristics necessary to assure a valid test in relation to present and future Navy subsystems; and (2) data procurement and analysis time must be consistent with the project's time frame. The more important criteria dealt with availability of effectiveness requirements, documentation on operating and maintenance requirements and the functional complexity and representativeness of a subsystem relative to other current and proposed Navy subsystems.

The original selection group was composed of 29 Navy subsystems representing air search radars, surface sonars, sub-surface sonars and fire control subsystems. After several evaluations based on the selection criteria, the AN/SPS-30, AN/SPS-40 and AN/SPS-43 air search radar subsystems were found to be equally satisfactory. In conjunction with Navy BuPers representatives, the AN/SPS-40 was finally chosen as the most feasible and potentially useful subsystem for use in developing and testing the standards derivation method.

B. Summary of Procedure Employed

The procedural format, developed in part during the trial application and used to establish standards for the AN/SPS-40, is presented in Appendix B and consists of the following steps:

- Collect Data
- Define System Input and Output States
- Determine System Functions
- Prepare Graphic Model Data Form (GMDF)
- Construct Graphic State Sequence Model (GSSM)
- Construct Mathematical State Sequence Model (MSSM)
- Allocate Requirements to PEF Units

C. Appraisal

Results of method application warrant a highly optimistic outlook, although there are some theoretical deficiencies that have yet to be overcome, particularly in the area of requirements allocation.

Much system functional and structural data were needed to construct the Graphic State Sequence Model. There were some difficulties in locating all the necessary documentation required because system effectiveness requirements for the AN/SPS-40 have been defined only in a gross sense. A minor difficulty arose in setting limits (i.e., stating the appropriate input and output states) to that portion of the radar subsystem which we felt could be handled in the time available and at the same time provide a good challenge to the methodology.

Constructing the GSSM definitely requires training in concept and procedure. However, we have demonstrated to our own satisfaction that such training can be accomplished economically. In the course of studying and applying instructional procedures, notes were kept concerning the important issues involved in communicating principles of GSSM construction. Those notes in turn were refined and organized into the systematic format presented in Appendix B.

Of particular importance in GSSM structuring is the need for a searching, open-minded attitude combined with an understanding of what all aspects of the system can do. System design must not restrict the analyst's thinking as to how the system is purported or expected to perform. Instead, the essential question must concern what the system is capable of doing under various circumstances. Once the GSSM was constructed, the mathematical modeling technique was applied without difficulties.

Human reliability information from the "data store" developed by Payne and Altman[1] was used to "score" the AN/SPS-40 PEF Units and therefore provide a basis for requirements allocation. The limitations of using that approach have been described in Section III-E.

Aspects of allocation not considered in the application were: (1) treatment of alternative procedures for arriving at a given system state; and (2) requirements other than probability of accomplishment (e.g., performance time or accuracy). The first aspect resulted from the large number of alternative procedures which could exist within the AN/SPS-40 that will lead to the same (or a highly similar) system state. Since the principal purpose of the application was to develop and test the method rather than to perform a complete analysis of the AN/SPS-40, it was decided that the purpose could be served most efficiently and effectively by considering only the system's principal activity. The process for allocating system requirements among the alternatives would, in any case, follow the methods detailed in Section III-B and Appendix B.

A test of requirements allocation in terms other than probability of accomplishment was not carried out since the scope of the study did not include complete development of multi-dimensional allocation techniques. It is felt that the application adequately tested the method through attention to the effectiveness requirement with the greatest potential utility -- probability of task accomplishment. In light of the successful application of the method to the AN/SPS-40, there is every reason to expect that the technique can be applied successfully to a wide range of Navy systems for which adequate input data are obtainable. Complete and currently accurate information regarding a given system is necessary to apply the graphic and mathematical models.

The approach to method development included constant consideration of the anticipated needs of the person who is to apply the technique. As a result, any capable and interested person should be able to learn to use the technique once it has been fully developed. In its present state of development, the modeling tasks have been defined in detail and should present no problem in application. However, due to the absence of a comprehensive set of behavioral data, and a fully developed allocation procedure, the allocation process cannot be considered a routine task.

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[1] Payne and Altman, op. cit., 1962.

VI. POTENTIAL USES OF THE METHOD

The job standards method, following comprehensive methodological development and testing, can be expected to have application as a general research tool in system design and development in addition to its perhaps more obvious and immediate role in personnel research. Potential applications in those two areas are described below.

A. Personnel Research and Management

Application of the job standards method provides a body of performance standards or criteria that reflect actual performance requirements of the system for each identifiable personnel/equipment functional unit. Consequently, the method's potential in the area of personnel research and management (selection, assignment, organization, training and evaluation) is extremely broad. Several specific uses of the method in this area are:

- Establishing performance standards for use as selection criteria in manning a system.
- Setting training standards for BuPers, Fleet Schools and OJT.
- Deriving criteria for evaluating human engineering design, training effectiveness and personnel preparedness.
- Developing sampling plans for proficiency test construction to assure that the test reflects critical job requirements.
- Establishing qualifications for advancement in rating tied directly to level of contribution to system operation.
- Stating alternative expressions of standards to meet specific user needs, e.g., designers, personnel research personnel, training specialists, etc.
- Developing occupational hierarchies for personnel subsystems. (See Section VI-C.)

B. System Design and Development

The basic application of the job standards derivation method in this area concerns trade-off analysis and testing compatibility within various sytem design concepts. The major area of attention would be personnel design; although consideration of equipment design and system goals in the trade-off context are also amenable to analysis.

Among the potential uses of the method in system design and development are:

- Identification and appraisal of various design and support approaches for achieving stated system goals.
- Man-machine function allocation trade-off studies.
- Allocation of personnel and training resources.
- Identification of specific areas for emphasis in system test and evaluation and for use as a basis for interpreting test results.
- Specification of operating procedures and implications for maintenance activities.

Also, the method is equally applicable to existing systems when the objective is apt to be related to determining and evaluating optimal approaches for upgrading and improving system effectiveness under relatively fixed design constraints. Some specific areas of application on existing systems are:

- Identification of areas for emphasis during system evaluating and for diagnosing expected payoff from remedial action.
- Testing the adequacy of existing personnel performance specifications in meeting system effectiveness goals.
- Determination of the effects of alternative personnel performance levels, procedures, sequences, etc. on system effectiveness goals.

C. Occupational Hierarchy Development

In Section V-A, it was suggested that the job standards method could be extremely useful in developing occupational hierarchies for personnel subsystems. In this section, a preliminary investigation of the potential usefulness of the method for that purpose is reported.

1. Initial Considerations

There are two basic directions that could be taken in using the job standards method to develop an occupational hierarchy for a system: (a) concentrate on the personnel needs of the system to the exclusion of any existing occupational structure; or (b) attend primarily to relating analyzed system needs to an existing formal occupational hierarchy.

In the first case, the body of job standards and behavioral descriptions could be used to provide, ultimately, a classification of the behavioral demands on the system to satisfy system goals. That use would provide the basis for a unique, current-state hierarchy of Naval personnel position requirements if it were integrated over a number of similar Navy systems. If behavioral descriptions from a number of systems were collated, the relations among the behavior clusters (positions) could lead to an occupational hierarchy based on current system needs for personnel performance rather than on skill and knowledge available.

The profit of such a "system-needs" oriented hierarchy is a function of the manner in which it would be constructed. As an integration of current and planned systems, it reflects the dynamic requirements of personnel activities. A formal occupational hierarchy is principally a reaction to technical needs, since it is predicated on skill and knowledge availabilities (for example, the NEC/NOBC). In some cases both hierarchical types may be coordinated into a single occupational structure and, as such, facilitate personnel subsystem allocation, training and development.

In the second case, the job standards method would be used to develop personnel position structure for a given system within the framework of current personnel classifications. That approach offers immediate profit and is detailed below. Regardless of which case is selected finally, the difference between cases is more conceptual than technical.

It was planned early in the term of the study, that an occupational hierarchy would be developed for the AN/SPS-40 radar subsystem as both an illustration and a test of that use of the job standards method. Due to the relative simplicity of the portion of the AN/SPS-40 subsystem selected for analysis by the job standards method, particularly with respect to the total number of activities required by the subsystem, an application of the procedure described below for developing an occupational structure did not seem justified. For application and test of the procedure to be meaningful, a more comprehensive body of PEF Units and performance standards is required.

2. Approach

Our general approach to the problem of personnel position definition is along traditional lines, although it differs in two principal areas: (1) system data sources, and (2) rank ordering PEF Units by an index of system "criticality." The source of system data from which personnel requirements are derived is not the "typical" system analysis but rather the job standards. To relate the personnel requirements of a Naval system to personnel classifications, the activities performed by each personnel position must be available. In the job standards method framework, those personnel activities are behaviors included within each PEF Unit, and are obtained either from the descriptions associated with each PEF Unit or from the GMDF.

Data about the types of positions required by the system are also necessary to our development of an occupational hierarchy. That information is obtained from the GSSM. Whether the system being analyzed is operational or still in the design state, the GSSM, presented against a time-line, permits identification of the minimum number of positions necessary. That identification is made without regard for the general skills and knowledge required by any one PEF Unit, and without regard for special or environmental constraints. When those additional factors are known and relevant, positional requirements may be modified. Factors of that nature, when they are identified as essential to meeting system requirements, would already be a part of the GSSM.

In addition to the first two kinds of information discussed, the occupational hierarchy procedure requires a means of ordering the behavioral descriptions used, in relation to occupational classes. The ordering is made along the dimension of "criticality." The concept of criticality is not new to systems analysis methodology. However, while the concept receives little formal treatment in most methods, it is an integral part of the procedures of the job standards technique.

It has been mentioned elsewhere in this report that PEF Units included in the standards derivation are only those activities necessary and sufficient to the goals of the system. Therefore, even though PEF Units are equally essential (i.e., they are necessary and sufficient), they may be distinguished by their patterns of magnitudes along several dimensions; as for example, probability of required success, time, and accuracy. Positions of PEF Units on those dimensions permits ordering PEF Units to facilitate decisions of personnel trade-offs. The rank order of any one PEF Unit along such dimensions is referred to here as its index of criticality (Cr_i), such that:

$$Cr_i = f(P_i, T_i, V_i, A_i)$$

where:

P_i = the success probability required

T_i = the time required

V_i = the recoverability from error, and

A_i = the tolerances, or precision, required.

In other words, Cr_i is principally a function of the job standard components associated with each PEF Unit. Thus far, in the development of the standards method, the function relating those factors has not been mathematically expressed to the degree required for use of a criticality index. As will be seen below, such an index would be used only to order PEF Units, not to quantify differences among them. The mathematical expression of the criticality function need not, therefore, be highly precise.

3. Procedure

An overview of the procedure is shown schematically in Figure 8. In the figure, and in the discussion below, activities are described in procedural steps.

Step 1

Establish minimum number of personnel positions. The GSSM indicates the sequence of personnel activities as they are appropriate to the system. To the degree that activities are ordered sequentially, they constitute one position -- that is, one person could conceivably perform the activities (within the limitations mentioned in the previous section). Each parallel display of activities -- as would follow the "and" (or dot) symbol, for example -- implies that an additional position may be necessary to accomplish tasks which can be performed concurrently. An additional position is always implied by the job standards when the time limitations for any one sequence of activities is greater than the summed time for two or more parallel sequences. Both situations are illustrated in Figure 9. Insofar as time is concerned, PEF Units 1 and 2 can be performed by one person, while PEF Unit 3 constitutes a second position.

Step 2

Obtain activity descriptions for each PEF Unit personnel behavior. As has already been mentioned, the information may be obtained from

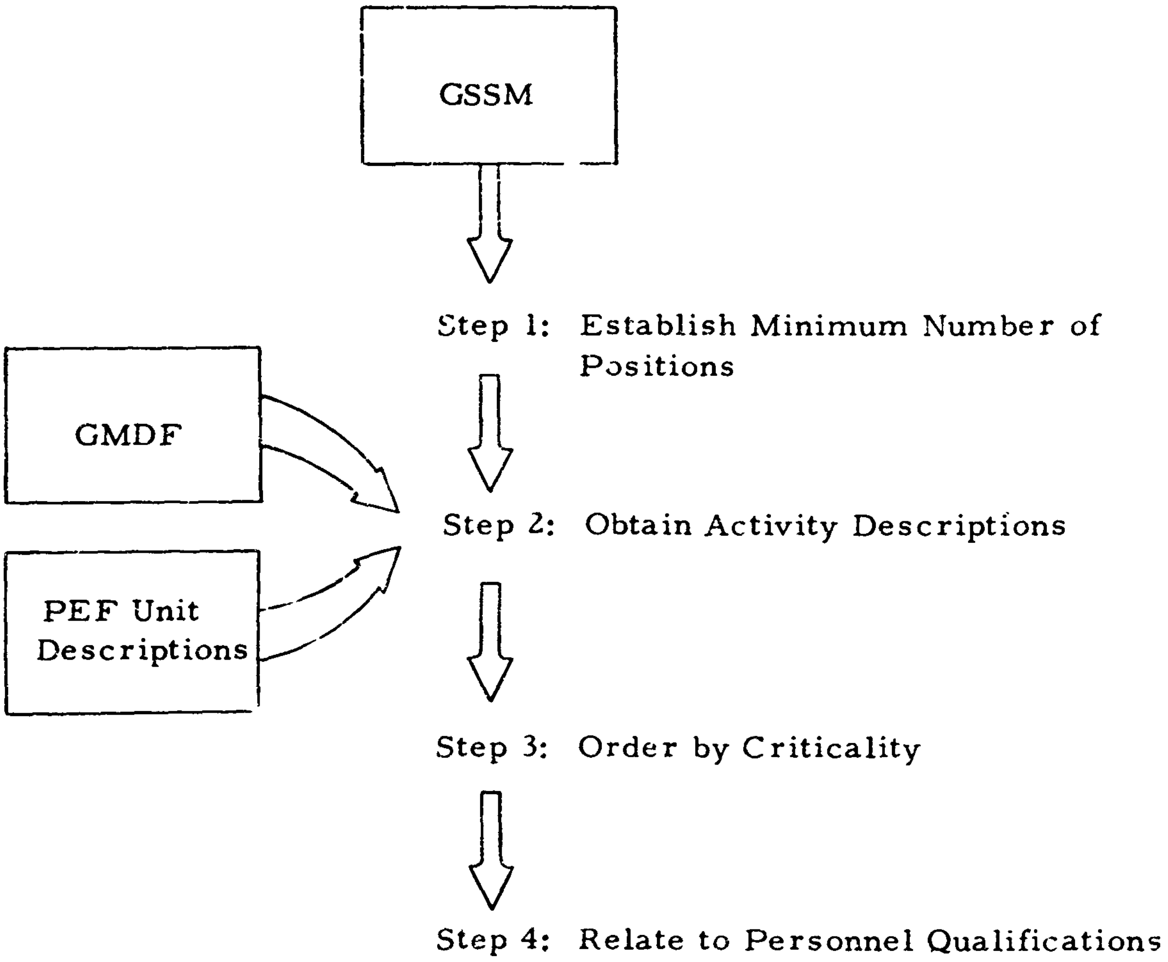

Figure 8. Schematic of general procedure for developing occupational hierarchies.

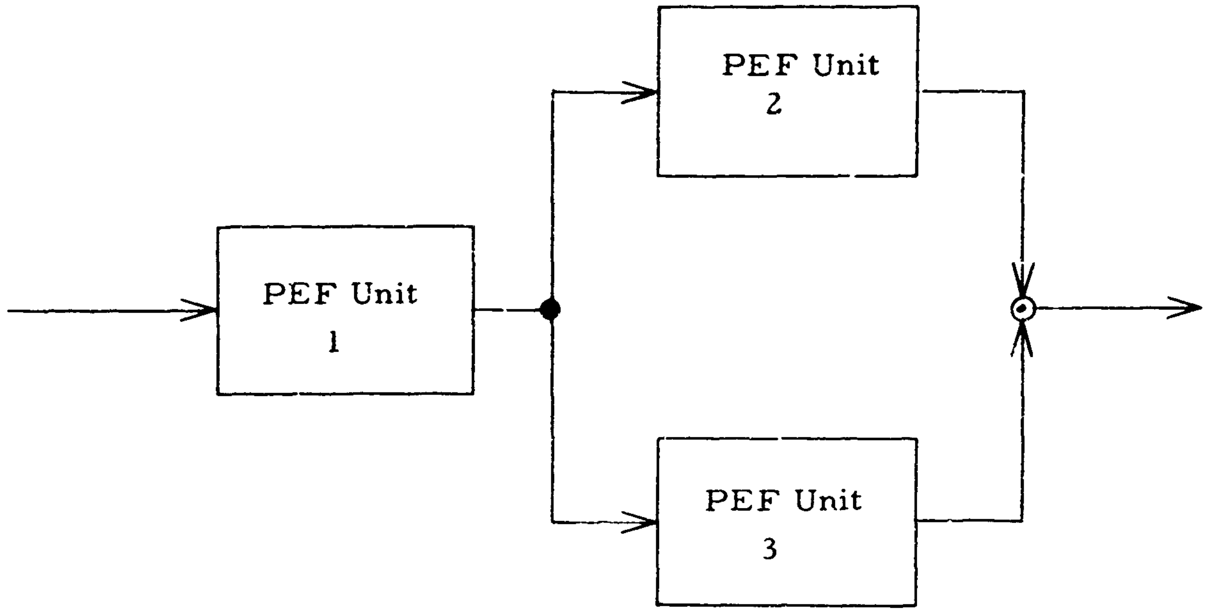

Figure 9. Hypothetical partial GSSM.[1]

either the GMDF or the description associated with each PEF Unit standard. The kind of activity description available is contingent, in part, on the original purpose for which the descriptions were developed. That is, the vocabulary and syntax of behavioral descriptions vary from use to use, since there is no currently accepted standard vocabulary. The vocabulary for job standards was developed within the context of various modeling techniques, with some slight modifications for use with data store information. As such, it is largely compatible with the activity descriptions presented as part of NEC qualifications

Step 3

Order PEF Unit descriptions by criticality for each personnel position. The absence of a firm method for obtaining a criticality index has already been discussed; suffice it to say here that the index will represent a synthesis of the variables making up the PEF Units standards. Interpretation of the ordering is as follows: while all PEF Units are necessary to successful satisfaction of system requirements, the more a PEF Unit is ranked as critical the more important it is that that PEF Unit be accomplished correctly in strict accord with the established job standards: because of (1) its irretrievable nature, (2) a low initial probability of success -- the lower the probability of success, the greater the impact on system performance of any change in probabilities, (3) the

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[1] State descriptions have been omitted for the sake of brevity.

impact on system performance of a change in its probability of accomplishment, or (4) the dependence of several other PEF Units on successful completion of the PEF Unit in question. All such factors are reflected in a "criticality" ranking of PEF Units. Specific utility of this step will become clear as the final step is discussed.

Step 4

Compare PEF Unit activities and rating qualification statements (in NAVPERS 18068A). Those qualifications for advancement appear, in part, as a series of factors within areas, such as (1) theoretical and practical equipment knowledge, (2) safety, operating and administrative procedures, and (3) maintenance. Within each area, behavior statements which describe a particular qualification are also presented, with the advancement level to which the qualifying behavior is relevant. While they are usually presented by factor, they can easily be reorganized by rating level (within specialist codes) to facilitate use in personnel assignment. Regardless of the format in which the qualification statements appear, PEF Unit activities and the qualification statements are compared to identify the qualification statement most like a given PEF Unit activity in all accountable respects. When a PEF Unit has been identified as most related to a given qualification statement, the associated rating level is noted. The list of ratings which results constitutes the personnel requirements for the system in question.

When the steps above have been completed a summary table, such as Table 2, may be constructed. The table displays direct information regarding the levels and kinds of specialist personnel required to man the system -- by PEF Unit as well as by position. The table also presents the rating distribution of skill levels for each position. In the example given, all activities for Position A may be performed by an RD2. Position B, however, has activities that are within the skill levels of several RD ratings. If an RD3 were given the position, PEF Units 4 and 6 would be beyond his skill level -- he would need at least OJT to bring him up to the required level of performance. At the other extreme, while a RD1 has all the skills necessary to fulfill the performance requirements, he is, to a degree, overskilled for the demands of the particular position. In this example, the most critical PEF Unit for Position B is, by definition, PEF Unit 4. According to the table, that activity can be performed by a RD2. The manning decision might be made, therefore, to specify an RD2 as minimum for the position, recognizing that he is overtrained for at least one activity and will require OJT for another activity. Without additional training, he can complete 66.6% of the activities required, including the two most critical ones.

Table 2

Hypothetical Relation of System Personnel Requirements and Ratings

Rating (for radar-man)	Position A			Position B		
	PEF Unit 1	PEF Unit 2	PEF Unit 3	PEF Unit 4	PEF Unit 5	PEF Unit 6
RDC						
RD1						X
RD2	X	X	X	X		
RD3					X	

4. Discussion

The principal use to which the occupational hierarchy development procedure may be applied is in effective assessment of the personnel requirements of a system as outlined in the preceding section. With the exceptions noted earlier, use of system personnel activities for that purpose is not unique to standards methodology.

The highly quantitative, system-activity-oriented data yielded by the procedure are unique. Immediate use of the data may be made in several potentially profitable ways, the foremost being in an attempt to assess the overall contribution of a particular position to the operational success of the system. Once personnel requirements have been determined, it would be a relatively simple matter to compute, for example:

- Proportion of activities performed (operator loading) by any one position, rating, group or individual PEF Unit -- in any combination,
- Manning costs, and
- Contribution of any position, PEF Unit or rating to overall system effectiveness.

Because the general occupation allocation procedure has not yet been tested fully the examples above are mentioned only briefly to illustrate the contribution to system planning that the procedure could make.

VII. ADDITIONAL RESEARCH RECOMMENDED

As was noted in Section I-B, the present study was devoted to developing a basic capability for deriving system-related job standards and for testing the effects of performance levels that deviate from established job standards on system effectiveness. Described below are several logically related task areas that are necessary to extend and refine that basic capability through additional methodological research, empirical testing and specific treatment of implementation and application problems.

A. Methodological Refinement

For the job standards method to realize its full potential, it is necessary that methodological research be continued to extend the basic capability of the method described in this report. The applicability of other mathematical techniques and procedures should be explored as well as further and more comprehensive testing of the method using actual system data.

1. Mathematical Development

Additional research is required in the area of requirement allocation techniques. It is evident that increased reliability and comprehensiveness in the basis for arriving at an index of accomplishment for the personnel/equipment functional units is desirable. Preferably, the indices would be based on objectively-defined characteristics of any system in its dynamic operation, rather than on discrete independent elements of system functioning. The indices should be able to serve at least three functions:

- As weighted values for deriving the probability components of personnel performance standards via the MSSM.
- As a basis for further development and verification of the techniques by utilizing feedback information from observations implied in the derivation of the indices.
- As a potential basis for evaluating (and incorporating where appropriate) human capability data from other sources.

The Index of Task Accomplishment (IOTA) eventually should be a multi-dimensional variable whose primary dimensions involve relatively stable characteristics of a given system, including man, for any duration and accuracy of operation. That is, for given time and accuracy constraints human and equipment characteristics are expected to vary extremely slowly compared to overall system performance. However, different time and accuracy constraints may result in significant changes in index values, particularly as those constraints become psychologically or physiologically stressful. Although this area has been investigated and several tentative hypotheses have been generated (See Section IV-B), additional effort is recommended to refine and test those hypotheses.

The present method rests on the application of conventional conditional probability theory to relate defined states of the system throughout its operation. There are other probability techniques for relating system states depending upon how they are to be used and the kinds of operations to which they relate. Those techniques should be evaluated and if they prove useful, th should be incorporated into the overall approach.

2. Integration of Maintenance Considerations

In the present study, it was determined that overall maintenance time requirements can be established readily from the system availability requirements if system failure rate is known. Also, it was determined that time requirements could be established for various categories of maintenance, defined in accordance with demands on maintenance personnel capabilities. In addition, it was found that maintenance actions can be modeled using graphic and mathematical state sequence modeling techniques which constitute the key elements of the basic standards method.

Additional effort is recommended to integrate maintenance considerations completely in the standards method, and should include:

- Performance of a detailed analysis of the general maintenance model,
- Determination of the most appropriate classification system for establishing detailed maintenance time standards,
- Determination of an appropriate index of task accomplishment for allocating standards to categories of maintenance. (It may be determined that one index of task accomplishment may be appropriate for allocating both operator and maintenance PEF Unit standards.)

3. Alternative Job Standard Expressions

As presently conceived, a job standard ultimately will be composed of a personnel/equipment functional unit (PEF Unit), an accuracy/time requirement and a required probability of successful performance. Alternative expressions of a performance standard may be required to fulfill the specific needs of several potential user groups. For example, a training specialist may be concerned mainly with a stated criterion performance level or interval of performance which his training program must meet. On the other hand, a systems design specialist, concerned with trade-off analyses, would be likely to require a probability distribution or expectancy data to be associated with a performance standard.

The capability to develop alternative job standard expressions is dependent upon progress in expanding the definition of a job standard to include various weighted combinations of objective measures, maximum/minimum performance statements, probability distributions as functions of accuracy or time permitted and other distributed functions.

4. Empirical Test of the Method

Data obtained on the AN/SPS-40 radar subsystem were employed, in the present study, to provide for on-going test and refinement of various elements of the method being developed. Use of actual data as an integral part of the development process was found to be a great value and it is recommended that that approach be continued in future work.

Two types of tests could be employed: vertical and horizontal. The vertical test consists of examining the method within the context of a single system such as AAW or ASW and its subsystems. (The AN/SPS-40 constitutes a subsystem of an AAW system.) The horizontal test, on the other hand, involves examination of the method across systems at the system or subsystem level. (For example, considering subsystems other than the AN/SPS-40 such as a navigation or sonar subsystem.) At present, it appears that vertical applicability of the method should be given greater emphasis than horizontal applicability. Therefore, it is recommended that test coverage be broadened within the AAW system context by considering other subsystems in conjunction with the AN/SPS-40.

B. Method Implementation

The problem of implementing a technique as comprehensive as the job standards method with its broad application is an important one. A carefully developed and thoroughly tested method would have little utility if implementing it is time consuming and laborious and its integration with existing programs is poorly effected. Consequently, this area deals with additional research designed to circumvent those potential difficulties.

1. Procedural Format

One of the products of the present study is a procedural format that ultimately will guide the user on a step-by-step basis in applying the method. As the method is refined, modified and improved, the procedural format must also be revised to reflect any changes and refinements. In addition, the procedural format should eventually be tested using a sample of Naval system's analysts to assure that it fulfills its purpose adequately. Ultimately, a user's guide for the job standards method should be produced that will instruct the user in all aspects of integrating the method in system design, development and test efforts, specify data requirements, computer applications, procedural steps, output interpretation and reporting techniques.

2. Integration with the Navy's RDT&E Process

If the potential of the job standards method as a system design and development tool is to be realized, definite steps must be taken to integrate it into the Navy's RDT&E process. One of the first steps in achieving that integration is to specify the input data requirements necessary for the method to be used to establish performance standards and to evaluate design trade-offs. Effort is recommended to develop a complete data requirements package that will detail the types of data required, levels of specificity, quantification form and when and how they should be collected and submitted during Naval system design and development. By specifying the anticipated data requirements of the job standard method as early as possible in its development, effective introduction of the method into the Navy's RDT&E process can be achieved with minimum time delay.

3. Use of Computer Techniques

Application of the job standards method, especially in design trade-off analyses, will involve a great deal of calculation. The greater the number of approaches, contingencies, qualifications and restrictions that need to be explored, the more complex the mathematical models will become. To obtain results rapidly and efficiently, computerization of the mathematical operations should be considered.

With the results of further development of the mathematical aspect of the method in hand, effort should be initiated to program those portions of the job standards method which involve substantial computation; i.e., those which have been found most laborious and time consuming using manual techniques. It is likely that existing computer programs will be applicable for some of the operations and any additional programs that might be required should be relatively simple to design.

VIII. GLOSSARY

A	Accuracy
Cr_i	A criticality measure of the ith PEF Unit
f( )	An unspecified function of the variable(s) contained in the parentheses
g( )	An unspecified function of the variable(s) contained in the parentheses
GMDF	Graphic Model Data Form
GSSM	Graphic State Sequence Model
i	(1) A symbolic index used to represent an integer or alphabetical character; it refers to one of a set of things. (2) The variable IOTA
I_a	That value of i (or IOTA) when there is no time constraint and the tolerance requirement -- if one exists -- is not varied.
I_α	The input state of the αth PEF Unit
IOTA	Index of Task Accomplishment
j	A symbolic index used to represent an integer or alphabetical character; it refers to one of a set of things
J	Difficulty of a job; a discrete variable
k	The constant for converting an IOTA value into the probability of accomplishing the associated PEF Unit
K	A proportionality constant associated with alternative procedures; the sum of the K values following a single CROSSED DOT symbol in the GSSM equals 1.0.
L	A required level of measurement tolerance (inversely related to accuracy)

m	(1) The uppermost of a number of values under consideration; an integer or alphabetical character referring to the number of things in the set under consideration (2) The number of repetitions of a set of PEF Units (3) One of a set of continuously variable measures (used in Section IV-B-5)
$\overline{m}$	The mean of a distribution of m measures
m'	One of a set of continuously variable measures having $\overline{m} = 0$
M	Man's capability; a discrete variable
MSSM	Mathematical State Sequence Model
MTBF	Mean Time Between Failures
MTTR	Mean Time to Restore
n	The uppermost of a number of values under consideration; an integer or alphabetical character referring to the number of things in the set under consideration
O_α	The output state of the α th PEF Unit
P	Probability -- often used instead of P( ), where the parenthetical portion is understood
P_i	Probability of accomplishing the i th PEF Unit
P( )	Probability of the occurrence (or of accomplishing) whatever is contained within the parentheses
P(in)	Probability of the input state
P(out) or P_o	Probability of the output state of the system or a portion of the system. Usually, it is understood that its value is given as a system effectiveness requirement
PEF Unit	Personnel/Equipment Functional Unit
P_iE_i	The personnel and equipment included in the i th PEF Unit

R_i	Time to carry out maintenance on the ith hardware item
S_c	An estimate of system output based on actual or proposed capabilities for performing component PEF Units
S_r	A system effectiveness requirement
SER	System Effectiveness Requirement
t	Time (variable)
T_i	Time required to accomplish the ith PEF Unit
T_{max}	A maximum value of time, t
T_{min}	A minimum value of time, t
T_T	The total time allowable for the system to reach its output state; a system effectiveness requirement
V_i	Recoverability from error of the ith PEF Unit
x	(1) Used in Appendix B to represent a PEF Unit (2) A symbolic index used to represent an integer or alphabetical character; it refers to a set of things
X	A symbol used in examples to represent an unspecified piece of equipment or an unspecified human, depending upon the context
y	Used in Appendix B to represent an input state
z	Used in Appendix B to represent an output state
α	A symbolic index used to represent an integer or alphabetical character; it generally refers to one of a set of PEF Units
Δ	A symbol representing a difference between two values; e.g., Δt may indicate an interval of time between t_1 and t_2

ϵ	A small positive increment of a numerical value
λ_i	Failure rate of the ith hardware item
π	3.14159
Π	Product symbol, indicating that all values following the symbol are to be multiplied together
σ	The standard deviation of a Gaussian (normal) distribution
Σ	Summation symbol, indicating that all values following the symbol are to be added together
τ	The time variable upon which a mathematical operation is performed
$\bar{\tau}$	The mean of a set of τ values
$<$	Less than...
$\leq$	Less than or equal to ...
$>$	More than ...
$\geq$	More than or equal to ...
∞	Infinity

Note: GSSM symbols are defined in Figure 2, page 18.

APPENDIX A

LITERATURE REVIEW BIBLIOGRAPHY

LITERATURE REVIEW BIBLIOGRAPHY

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APPENDIX B

PROCEDURE FOR DEVELOPING PERSONNEL PERFORMANCE STANDARDS

I. INTRODUCTION

A. General Remarks

The purpose of this Appendix is to present preliminary procedural steps and rules for implementing a method for establishing personnel performance standards to meet system effectiveness requirements. Since the method is still in the developmental stage, the procedures are rough and incomplete; much more work needs to be done before they can be refined. However, they reflect the progress that has been made to date.

The organization of subsequent sections of this Appendix follows the general outline of approach shown in Figure I-1. Use of the procedures included here rests primarily upon three basic assumptions: (1) the user has experience in systems analysis, in general; (2) the user is very familiar with the specific system being analyzed, to the extent that he can fully utilize the available data describing the system, and (3) the procedures are to be applied to the analysis and evaluation of existing systems, in contrast to aiding design.[1] The requirement for familiarity with the specific system is important because the analyst must be able to perceive the system's capabilities objectively without being constrained by the performance expected of it. That is, he will be called upon to recognize if the system might perform in ways other than those (1) recorded in documents such as operational procedures, or (2) carried out in actual practice.

Our technique depends primarily upon a knowledge of general procedural rules which may apply at any time throughout the construction process. Examples of application are presented. Common situations, rather than specific systems or subsystems, are employed as sample personnel/equipment functional units (PEF Units).

B. Definitions

- System - A system is an operational set of components delineated by its input state, required output state, and constraints. A system includes all features of the set which are effected by the transition from input state to

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[1] Procedures for utilizing the method in designing new systems can also be developed, and would constitute a logical extension of the work described in the body of the report.

OUTLINE OF APPROACH

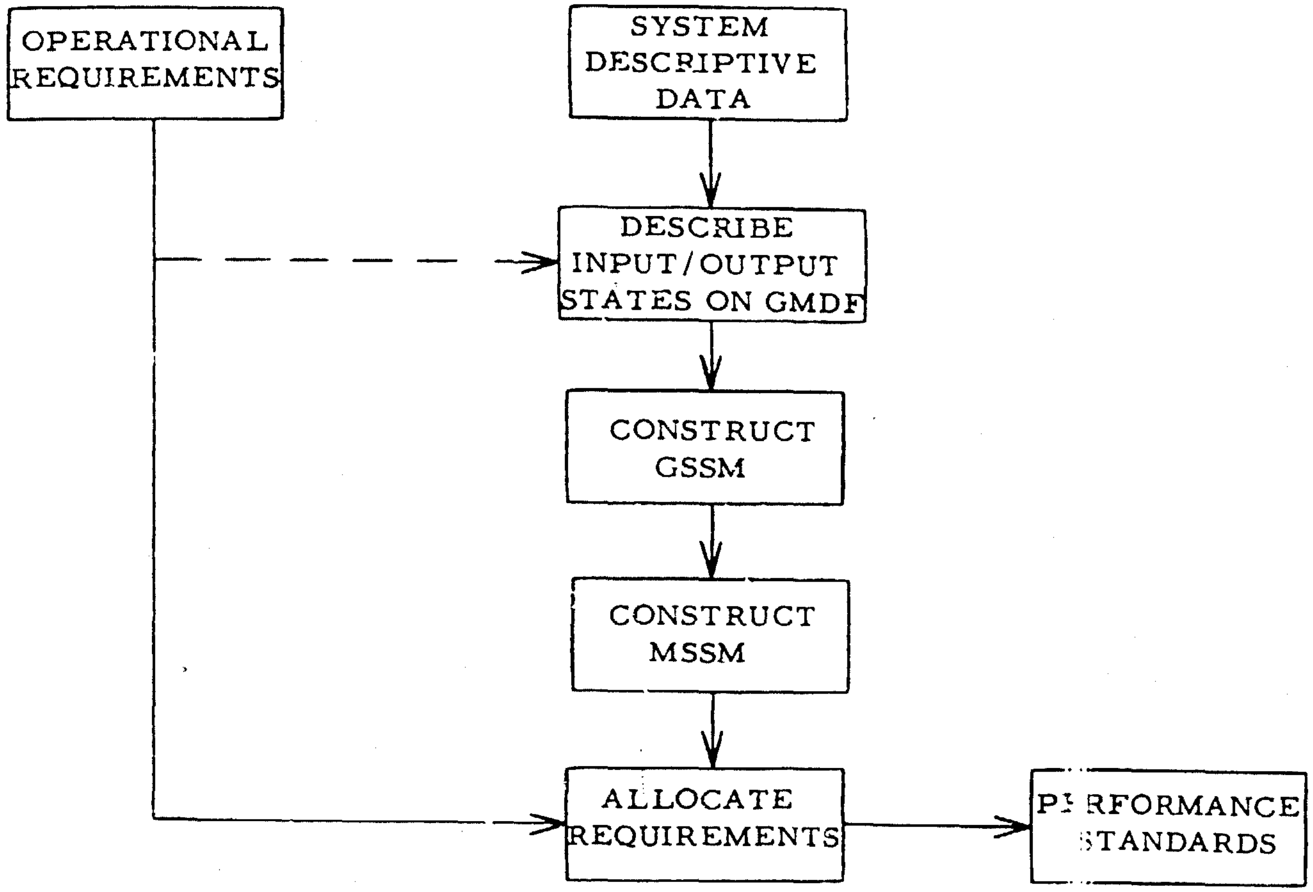

Figure I-1. Outline of approach.

output state within the constraints imposed upon it. A system can be represented graphically as a single (complex) personnel/equipment functional unit (PEF Unit).

- PEF Unit - A personnel/equipment functional unit is a general term indicating man-machine interaction at any level of specificity, depending upon the context of discussion. As opposed to a state, a PEF Unit represents one or more operations, activities or processes.

- State - A state of a system is identified by a complete description of the relevant and measurable characteristics of the system at an instant in time. (The description of the state is always a declarative sentence including the word "is" or "are", e. g., height and weight of pilot X are recorded on form P.)

  - The input state of the system is specified by initial system conditions which can undergo change during system performance; a change may occur at any time in the system's operation until the output state is reached.

  - Relevant features of intermediate states (between two or more PEF Units) are all the instantaneous conditions of the system which have undergone change as a result of the immediately preceding operation (i. e., prior PEF Unit). While only changed features are described for intermediate system states, all prior conditions are assumed. That is, the description of a state implicitly includes all unchanged portions of the system input state and the last-described condition of all features which have been altered from the system input state.

  - The output state is specified by the overall system requirements. It includes objective statements indicating the accomplishment of the system's objectives.

- Function - The broadest description of system operations is made in terms of functions. A function is a PEF Unit which is immediately related to the system mission such that a more general level of system operation cannot be specified. The system function is developed apart from and without regard to the specific hardware of the system being described. As a rule, systems with similar missions will have similar functions.

- Element - An element is alternatively called an elemental PEF Unit. It represents the most specific level of system description to which these procedures are designed to be applied. The complete definition of an element was developed in accordance with the rules for constructing a Graphic State Sequence Model (GSSM). Those rules appear in Section III. (The remainder of Section I is a detailed definition and explanation of an element. The reader may skip to Section II and study Sections II and III before completing this section.)

  1. The PEF Unit involves an interaction between a human and either (a) an inanimate feature, or (b) another human. Reiteratively, the action does not lie solely within a single human (e.g., thought or pure muscular response, such as lifting the arm) nor does it lie solely within the system (e.g., current supplied to a circuit).

  2. One or more of the following conditions must apply:

     (a) The input state of the PEF Unit is the system input state.

     (b) The output state[1] of the immediately preceding PEF Unit has more than one defined part[2] or alternative, not all of which form all or part of the input state of the PEF Unit under consideration.

     (c) The input state includes a feedback component which is not of a "re-do" type, i.e., the feedback does not imply that the PEF Unit is to be performed either

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[1] Throughout the definition, "output state" refers only to that required by the system.

[2] Whenever the word "part" is used in connection with the input or out-state, we assume the diagrammer's vantage point. "Part" refers either to (a) a portion of the total required state, or (b) one, two or more various required states.

because the action has not yet been completed or because it was not done properly.

(d) The input state comprises more than one component, each of which represents at least part of the output state of another PEF Unit.

(e) The input state is identical to the output state of an immediately preceding PEF Unit only if one of the following applies:

  (1) The unit under consideration fulfills requirement 4(b).

  (2) The immediately preceding PEF Unit fulfills requirement 4(b).

3. Somewhat overlapping Condition No. 2, one of the following must apply:

(a) The output state of the PEF Unit is the system output state.

(b) The output state forms part of the input state to a subsequent element.

(c) A part of the output state forms all or part of the input state to a subsequent element.

(d) The total output state forms the total input state to a subsequent element only if one of the following applies:

  (1) The unit under consideration fulfills requirement 4(b).

  (2) The subsequent element fulfills requirement 4(b).

4. One of the following conditions must apply:

(a) Any further fractionation of the PEF Unit under consideration will result in a failure to meet one or more of the requirements above.

(b) Further fractionation of the PEF Unit under consideration fails to meet requirements 2(b), 2(c) and 2(d), and/or 3(b) and 3(c), but the same PEF Unit appears somewhere else in the system description where it satisfies requirements 1, 2(a) through 2(d), 3(a) through 3(d), and 4(a).

To illustrate application of those criteria, a hypothetical element GSSM is shown in skeletal form in Figure I-2.

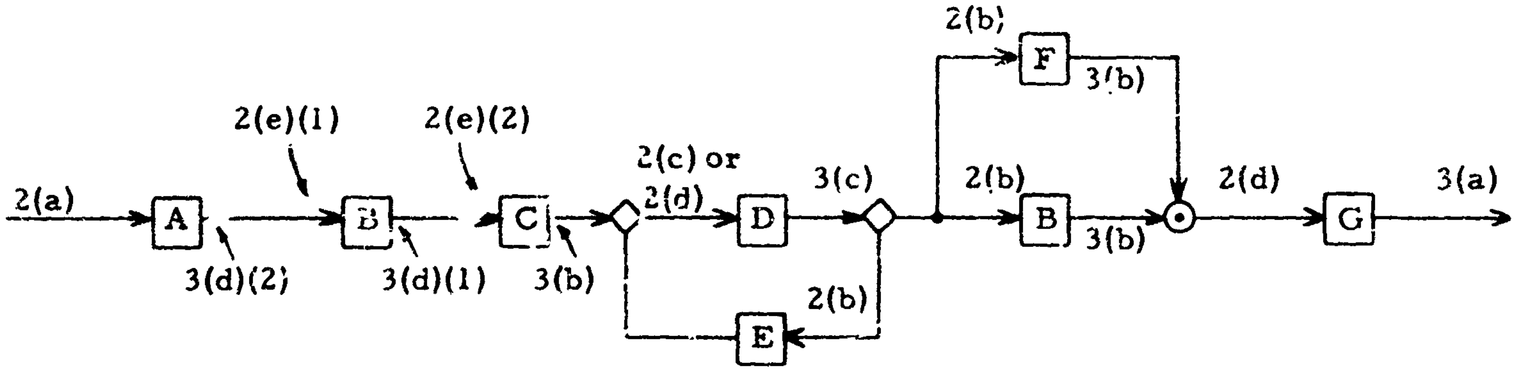

Figure I-2. Hypothetical skeletal GSSM illustrating the criteria for depicting a PEF Unit at the elemental level.

It is assumed that the diagram represents a system, or a portion of a system, and that all PEF Units, A through G, involve a man's interaction with either a piece of equipment or another man (thereby satisfying requirement No. 1).

The PEF Units are connected by lines which represent the system states at the respective points in the system operation. It may be noted that there are two possible output states after PEF Unit D, only one of which can occur during a single operation of the system; one alternative is the input state for E, the other is the simultaneous input state for B and F.

The numbers and letters which appear on the connecting lines in Figure I-2 reference paragraphs in the criterion definition for an element PEF Unit. As an example, therefore, the input state for A satisfies requirement 2(a), while the output state for A reflects paragraph 3(d)(2). It will be noted that if 2(e), 3(d) and 4(b) were omitted, the string of units, A-B-C, would not satisfy No. 2 or 3, thereby demonstrating the effect of 4(a). However, B occurs elsewhere in the system so that it fulfills the requirements of 4(b). We assume that we can demonstrate that none of the other PEF Units except B can be fractionated further without violating one or more of the requirements.

The importance of delineating meaningful elements of system performance rests on the fact that human activity can be reduced theoretically to an underlying set of neuromuscular and molecular changes. However, one might spend much time trying to define a system at that level without ever arriving at a means for establishing standards. It is necessary, therefore, to state system behavior only to that describable and measurable level necessary and amenable to an effective methodology. In our approach, the element PEF Unit represents that minimum level; it is definable according to non-behavioral, relatively objective criteria relating to construction by logical diagramming. Any further attempt at moving to a lower level would have no effect on the basic structure of the descriptive mathematical model we wish to derive from the GSSM at the element level. It is the mathematical model, not the GSSM, which provides the basis for determining probabilities (for standards) associated with system performance requirements, so procedural efficiency is unnecessarily abused by erecting a more complex GSSM than is required by the mathematical model we wish to derive. However, since the mathematical model will be derived directly from the graphic model, the latter must be complete and accurate for the mathematical statement to represent the system faithfully.

II. ORGANIZING DATA ON GRAPHIC MODEL DATA FORMS

A. Preparation and Purpose

Construction of the Graphic Model Data Form (GMDF) is an organizational process. It depends upon thorough familiarity with the system. In order to proceed, the analyst must have access to all available system descriptive material, including its operational requirements. (See Step 1 under B below.)

The purpose of the GMDF is to organize whatever information is already generated regarding the human contribution to system performance in a format that will facilitate subsequent modelling operations. Generally, the information necessary for constructing the GMDF is likely to be available in the form of operational procedures for a system which already exists.

B. Procedural Steps at the Function Level

Step 1

Prior to using the Data Forms, list the following information:

a. Overall system effectiveness requirements
   - The precise output (final) state of the system
   - Tolerances, or accuracy requirements, associated with each feature of the output state
   - Time limitations from onset of system functioning (if applicable)
   - Probability required for the output state components and their tolerances to exist when the system has completed its functioning

b. Input state conditions, i.e., complete descriptions of the relevant system just prior to its initiation.[1]

c. Complete characteristics of the system at any intermediate stage of its operation for which effectiveness requirements have been established.

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[1] See definition of input state.

- Describe altered conditions (from that in Step 1.b. and from prior intermediate conditions)
- List measurable characteristics of the system with tolerance requirements
- Time limitation, if applicable
- Probability required to achieve the specified system state

d. System constraints, either specified or assumed.

Step 2

Figure II-1 illustrates the recommended headings for the GMDF columns. The meaning of those headings will be clarified in the subsequent discussion.

Graphic Model Data Form

Function ______________________________

PEF Unit Number	Prior Necessary Step(s)	Alternate Step(s)	Activity Description	Output State	Imposed Requirement

Figure II-1. Recommended headings for the GMDF.

On the first GMDF, cross out "Function" and write "System" at the top. This data form will contain the initial breakdown of the system into Functions. Divide the system into as many Functions as possible, in accordance with the definition in Section I. B. (Some or all of the system conditions between functions may already have been delineated in Step 1, c.)

a. Assign a capital letter to each function, starting with "A" and place those letters under the heading "PEF Unit Number."

b. Under "Prior Necessary Step(s)" list the function(s) required in order that the needed input state exists. For example, if PEF Units B and C are parallel functions coming after A, then the prior necessary step for both B and C will be "A", because A provides the required input state for C as well as for B. (See relation No. 3 in Figure III-2 on page B-16.) Similarly, if A and B together produce the input state for C, then A and B are both listed as the "Prior Necessary Step(s)" for C. (See relation No. 2 in Figure III-2.)

c. List whether alternate functions exist ("yes" or "no"). In the examples above, state "no" for all three functions. However, if B and C are mutually exclusive, then "yes" should be indicated in the column headed "Alternate Step(s)" for both B and C. (See relation No. 4 in Figure III-2 on page B-16.)

d. Under "Activity Description" name the Function in a single word verb, or a brief verb phrase, indicating the general operation; e.g., "detect," or "determine distance to target."

e. Specify the output state of each function in relation to its input state; i.e., describe altered conditions from prior specified (and implied) conditions.

f. Under "Imposed Requirement" enter the reference number of the related system effectiveness requirement from the list prepared in Step 1.c., if indicated.

Example

The following hypothetical example illustrates the technique in skeletal form in order to be brief. A more complete example would give detailed data, but would require more space than is justified to demonstrate the use of the procedures.

System: Bench checkout of electronic item X (checkout procedures available)

a. Requirements

1) [The list of criteria to be met within specified tolerances] (In a realistic example, those criteria and tolerances would actually be stated.)

2) Time limitation for entire checkout of X = T minutes.

3) Probability required for successful checkout = P.

4) X is ready for installation.

b. Input state conditions:

1) [Checkout equipment] are available. (These should be itemized.)

2) X is on bench.

3) Technician has checkout procedure manual open to first page of instructions.

4) [Required power] is available at the bench (specify; e.g., 10 V.D.C.; 115 VAC, 60 cps).

c. [Intermediate characteristics] (In checkout procedures, these are generally specified by the output criteria, as listed under "Requirements" above.)

d. Constraints:

1) Room temperature is between y_1°C and y_2°C (for optimal performance by technician).

2) Sufficient time (T -0,+t) is available for complete checkout; technician is not likely to be interrupted while checking out X.

3) Checkout table is not made of any material which conducts electrical current.

4) Technician stands on rubber mat during checkout.

e. Establish functions:

Graphic Model Data Form

System ~~Function~~ Bench Checkout of X

PEF Unit No.	Prior Necessary Step(s)	Alternate Step(s)	Activity Description	Output State	Imposed Requirement
A	Input	———	Set up equipment	(Each piece of equipment listed with its required location)	
B	A	No	Supply power to equipment	(List all indications that equipment is ON)	
C	B	No	Checkout X	(List of measurement data specified in 3.a. 1) 2) & 3))	
D	C	No	Secure equipment	X is ready for installation	

C. Procedural Steps at the Element Level

One may proceed directly to the elemental level of system description, or one may describe PEF Units at a level of specificity intermediate between functions and elements. For large complex systems, intermediate levels may need to be generated in order to be able to manage further analysis accurately down to the elemental level. For example, "Bench Checkout of X" may be considered a subfunction of "Checkout" of a very large system which involves design, construction and checkout of many pieces of equipment.

The notation which is used to designate levels of specificity is illustrated in Figure II-2 below. Note that the first level refers to Functions and the last level to elements. A system may be analyzed to two or more levels, and different numbers of levels may be used for different systems. However, for any one system, the same number of levels should be used throughout the analysis. In the example to be presented later in this section, only two levels of specificity are indicated; B.3, for example, will represent the third element in Function B.

PEF Unit Notation	C .	1 .	2 .	5
Levels of Specificity	1	2	3	4
Example	Checkout	Bench Checkout of X	Supply Power to Equipment	Place ON-OFF Switch on X in ON Position

Figure II-2. The four levels of specificity of a four-digit PEF Unit (C. 1. 2. 5)

The Steps

1. At the top of the GMDF, identify the Function to be analyzed (with its name and code letter).

2. Referring to the operational procedures, assign a number to each procedural step. (For Function A, the first step would be A. 1, the second A. 2, etc.)

3. Under "Prior Necessary Step(s)" list the code number of the previous step(s) that must have been accomplished before this step can possibly be performed, according to the operational procedures.

4. Under "Alternate Step(s)" indicate whether or not an alternate approach may be taken to arrive at the output state.

5. Describe the man-machine operation clearly and completely under "Activity Description."

6. Under "Output State" describe all measurably altered features of the system resulting from the prior activity.

Example

Referring to the example begun under Section B.3., we will look at Function B, "Supply Power to Equipment."

Graphic Model Data Form

Function B. Supply Power to Equipment

PEF Unit No.	Prior Necessary Step(s)	Alternate Step(s)	Activity Description	Output State	Imposed Requirement
B.1	(Last step of Function A)	No[1]	Place AC switches to power supplies PS_1 and PS_2 to ON position. (Observe that AC ON lamps are lighted on PS_1 and PS_2.)	PS_1 and PS_2 are operative	
B.2	" "	No	Place ON-OFF switches to equipment G_1, G_2 and G_3 to ON position. (Observe that ON lamps are lighted on G_1, G_2 and G_3.)	G_1, G_2 and G_3 are operative	
B.3	" "	No	Press ON button on equipment G_5. (Observe ON lamp is lighted on G_5.)	G_5 is operative	
B.4	B.1	No	Three minutes after B.1, place DC switches to power supplies PS_1 and PS_2 to ON position. (Observe that DC ON lamps are lighted on PS_1 and PS_2.)	PS_1 and PS_2 are operative	
B.5	B.2 B.3 B.4	No	Place ON-OFF switch on X in ON position. (Observe that ON lamp is lighted on X.)	X is operative	

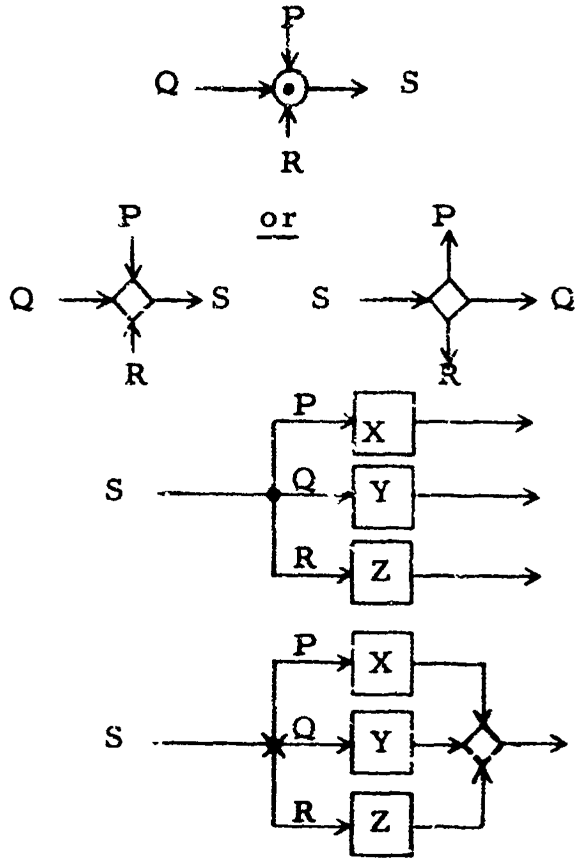
[1] While alternate approaches may be possible, if the procedures do not indicate that fact, none are listed.

III. CONSTRUCTING THE GRAPHIC STATE SEQUENCE MODEL (GSSM)

A. Introduction

The GSSM is a diagrammatic representation of the system. It specifies not only what the system is expected to do, but also what the system is capable of doing. As a result, the constructor must be thoroughly familiar with the system and all documents associated with it.

The GSSM comprises three primary components to symbolize the system processes and their interrelations: (1) "boxes" (or rectangles) represent operations, i.e., PEF Units, at any level of specificity; (2) lines connect the rectangles and represent instantaneous states of the system; and (3) connecting symbols are used to display relations among states. Definitions of the connecting symbols appear in Figure III-1.



AND symbol requires the simultaneous existence of two or more conditions for the subsequent action to occur; State S = State P plus State Q plus State R.

EXCLUSIVE OR symbol specifies that only one of two or more input or output states can exist at any one time; State S = State P or State Q or State R.

DOT symbol indicates that a single condition has two or more simultaneous effects; State S ≡ State P ≡ State Q ≡ State R and X and Y and Z occur.

CROSSED DOT indicates that a single condition has two or more possible effects, but specifies that only one of the alternative subsequent actions can occur; State S ≡ State P P ≡ State Q ≡ State R but either X or Y or Z can occur.

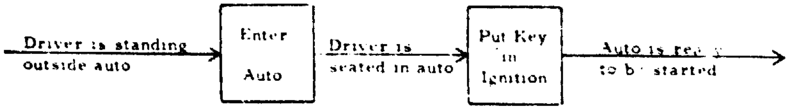
Figure III-1. Definitions of connecting symbols.

Figure III-2 demonstrates some basics of GSSM construction utilizing the three components.

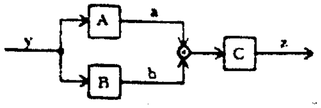
Relation | **Meaning** | **Example**

1.

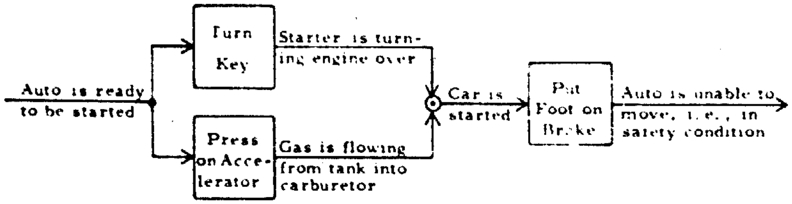
1. A must occur for B to occur; a is both the "output" state from A and the "input" state for B.



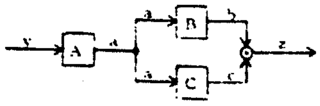
2.



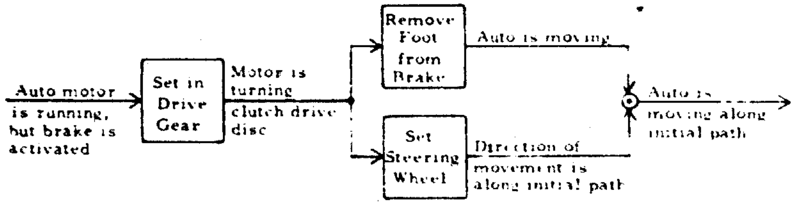
2. A and B must occur for C to occur. A may occur before, after or simultaneously with B. a + b is the "input" state for C.



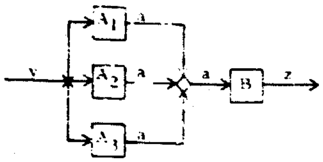
3.



3. A must occur for B and C to occur. B and C may occur in any order, or simultaneously. a is the "input" state for both B and C. z = b + c states.



4.



4. State a may be reached by any one of the three processes, A_1, A_2 or A_3 although not necessarily with the same efficiency or with the same degree of certainty.

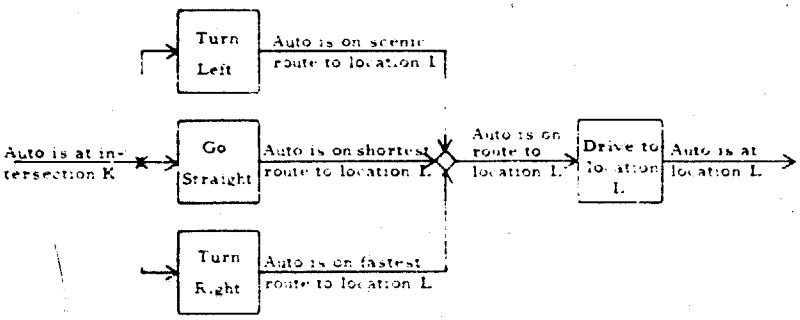


Figure III-2 Basic constructions

B. Procedures for Constructing the GSSM

1. Begin by representing the input state of the system by a line leading to one or more rectangles.

2. Using Figure III-3 as a general model of any single PEF Unit, proceed to draw the diagram, approaching each PEF Unit with the following series of questions and using the GMDF data as a guideline; the answer to each question must be "yes," for the diagram to be complete and accurate:

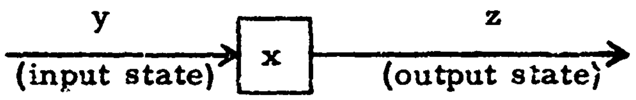


Figure III-3. A PEF Unit

a. Is it necessary to the system that x occurs?

b. Is y completely adequate for x to occur? (If additional input conditions are needed, those must be included.)

c. Is y just sufficient? That is, does the occurrence of x require the existence of the entire state described by y?

d. Is y worded so as to describe the state fully? Are all relevant features included as observable or measurable conditions of the system?

e. Does the diagram illustrate all occurrences to which y may give rise?

f. If x is not the only operation that might lie between y and z, for this particular system, are the alternatives also included?

g. Are alternative operations meaningful? (If alternative activities are possible - and they almost always are - determine which ones might reasonably be expected to occur sometimes, and which ones are only observed possibilities so as to be likely never to occur at all.)

h. Does z fully express the total change in the system resulting from x and only x?

i. Is z complete; that is, does it specify the alternative outcomes of x?

j. Is z worded so as to represent an observable, measurable condition of the system?

3. Illustrations of the use of the questions. Figure III-4 shows how the questions in Section III. B. 2. lead to correct GSSM construction.

4. Example at the Function Level

a. Referring to the sample GMDF of II. B. 2. e, the GSSM would initially appear as shown in Figure III-5, with system states clearly defined.

It is apparent that the functions (not the states) could apply to the checkout of any system involving electrically powered equipment.

b. Assume that some of the checkout of X must occur before power is supplied to the equipment; some of the checkout can occur before or after power is supplied and some must occur after power is supplied. In that event, Functions E and C are not clearly separable as indicated in Figure III-5. At the function level, however, Figure III-5 is still acceptable because it is primarily descriptive and satisfies the definition of a function (see Section I. B.); a more specific diagram would no longer be system independent.

A second breakdown may be needed to incorporate the new information. Figure III-6 illustrates how that would be done.

5. An Example at the Element Level

Referring to the example in II. C. 7., the GSSM would be constructed as shown in Figure III-7. In order to conserve space, note that the code numbers in the boxes of the diagram refer to the "Activity Descriptions" in the example of II. C. 7.

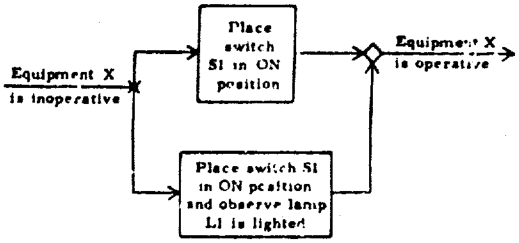
The features to be observed in the example are these:

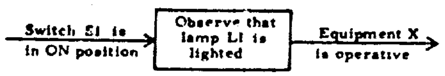
a. B. 1, B. 2, and B. 3 may be performed in any order sequentially, or simultaneously by different persons.

EXAMPLES OF APPLICATION

PRINCIPLE | **CORRECT** | **INCORRECT**

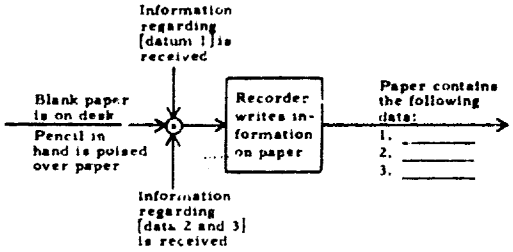
a. A PEF Unit which must be traversed in system operation MUST BE NECESSARY to system performance

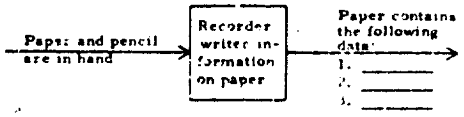




Equipment X cannot be operative unless S1 is ON, but it can be operative if lamp is not lighted or if operator does not see that L1 is lighted.

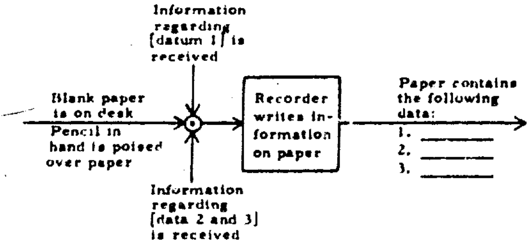
b. The input state must be completely adequate

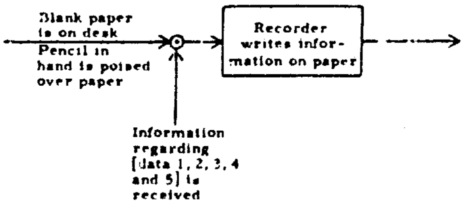




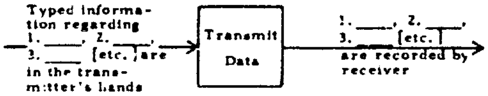
One cannot write information without having received it. The PEF Unit description itself calls for paper, pencil (or pen) and the data to be written down.

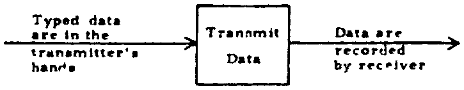
c. The input state must not be excessive for the occurrence specified by the PEF Unit



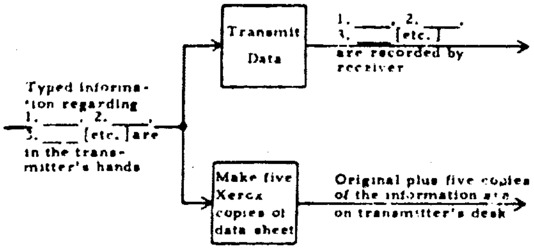


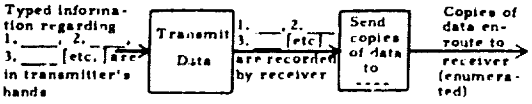
d. The input state must be worded so as fully and objectively to describe the state





e. The diagram must show all occurrences to which the input state gives rise





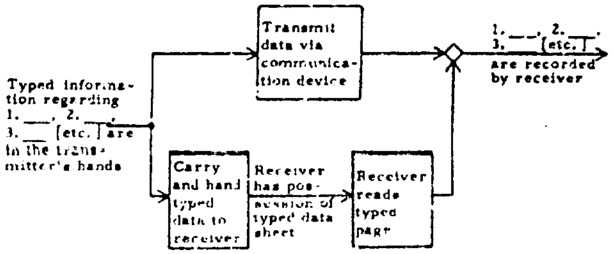
The copies cannot be sent until they are made, and the transmitter need not wait until he transmits the data before making the Xerox copies and sending them off.

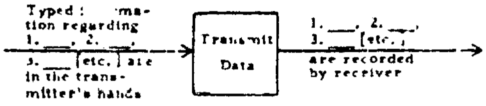
Figure III-4. GSSM construction principles.

(continued next page)

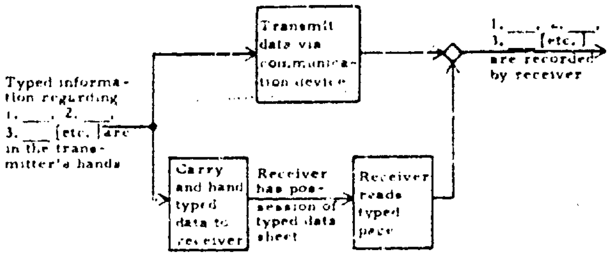
PRINCIPLE | CORRECT | INCORRECT

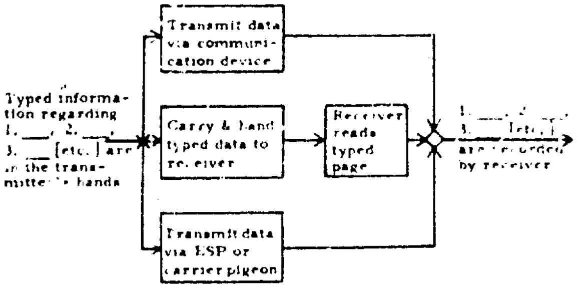
f. Alternative occurrences which could lie between the required input and output states must be included



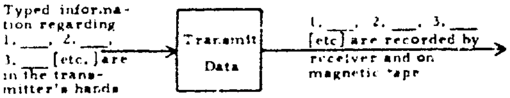


g. Alternative operations must be meaningful



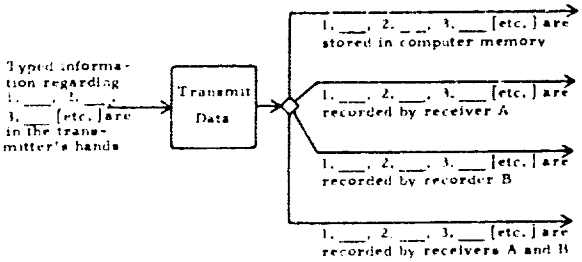


h. The output state must fully express the relevant changes in the system resulting from the PEF Unit



Investigation may reveal that later operations require someone to analyze the magnetic tape.

i. All meaningful alternative output states must be specified



The data may be transmitted in only one of four possible ways at a time.

j. The output state must be worded to represent an observable, measurable condition of the system

[see all above]

Data is nebulous. What class or kind of data must be recorded by the receiver? e.g., depth of submarine in feet, 1 x feet.

Figure 1.1-4 (Continued)

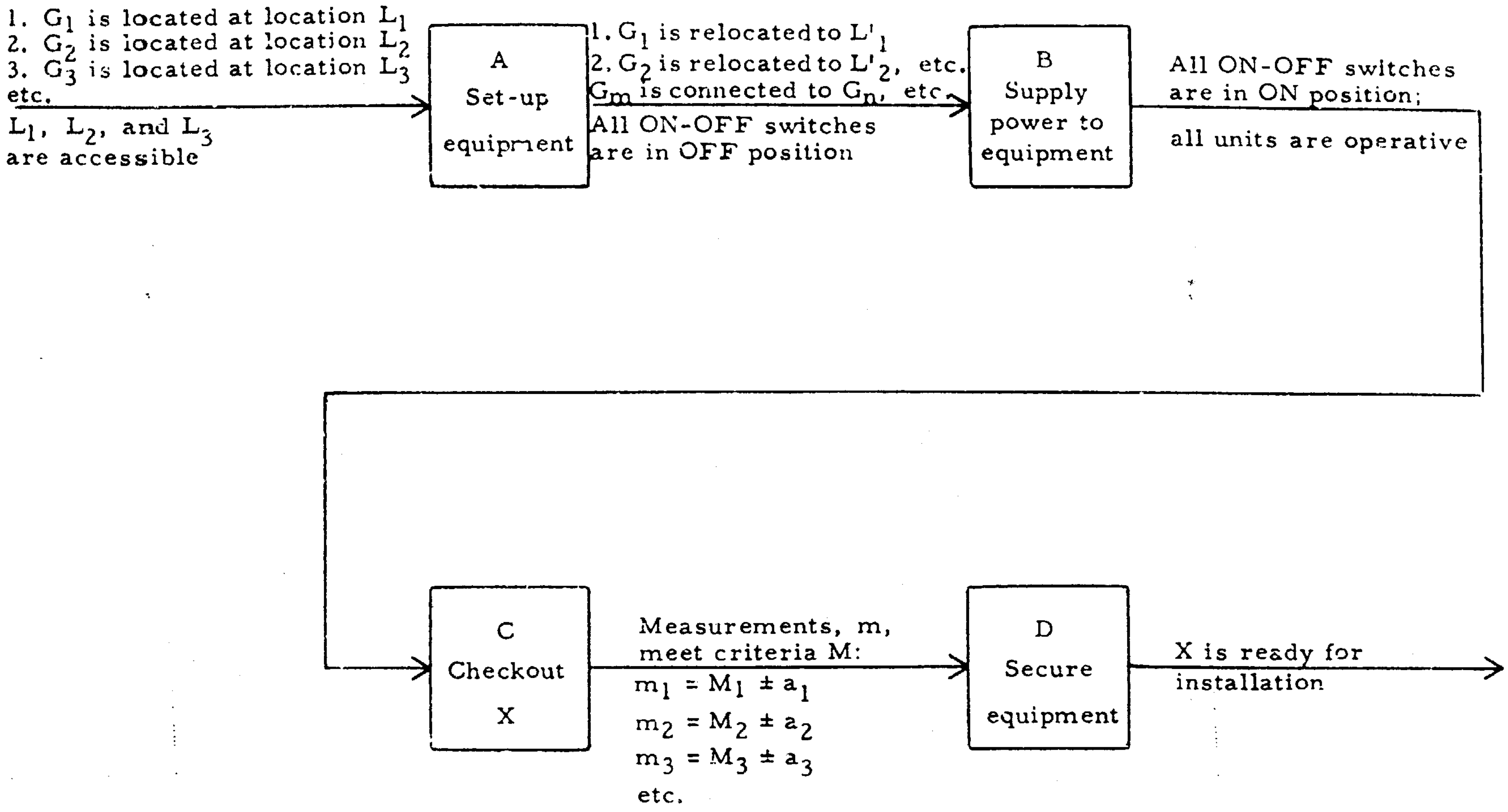


Figure III-5. GSSM of the Functions of a hypothetical system.

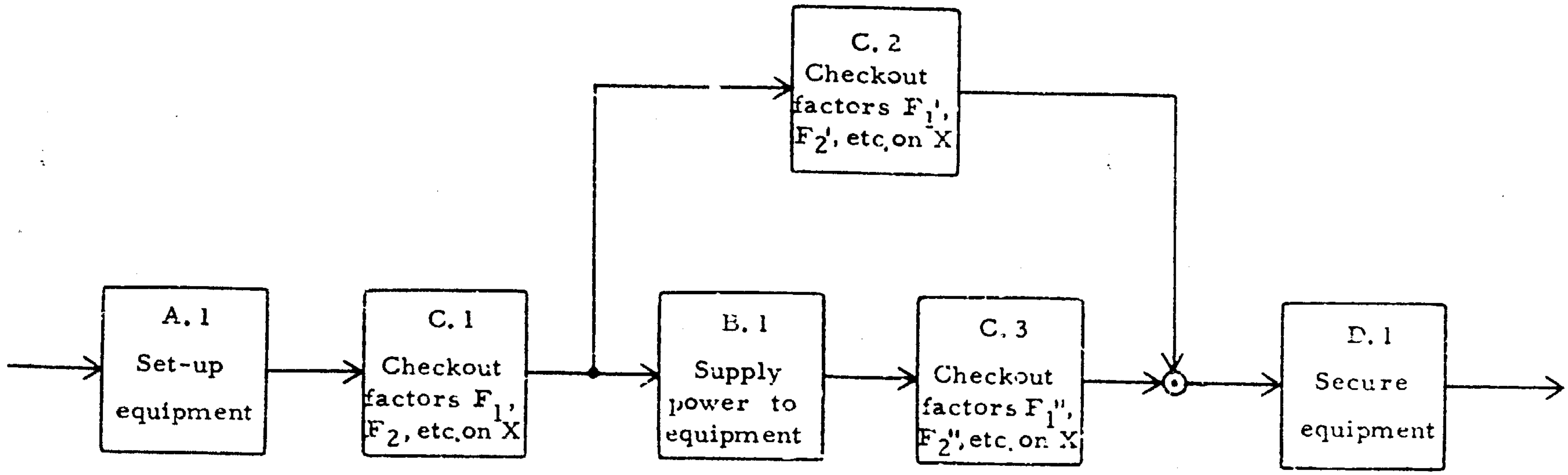


Figure III-6. Example of a possible second level GSSM (from Figure III-5).

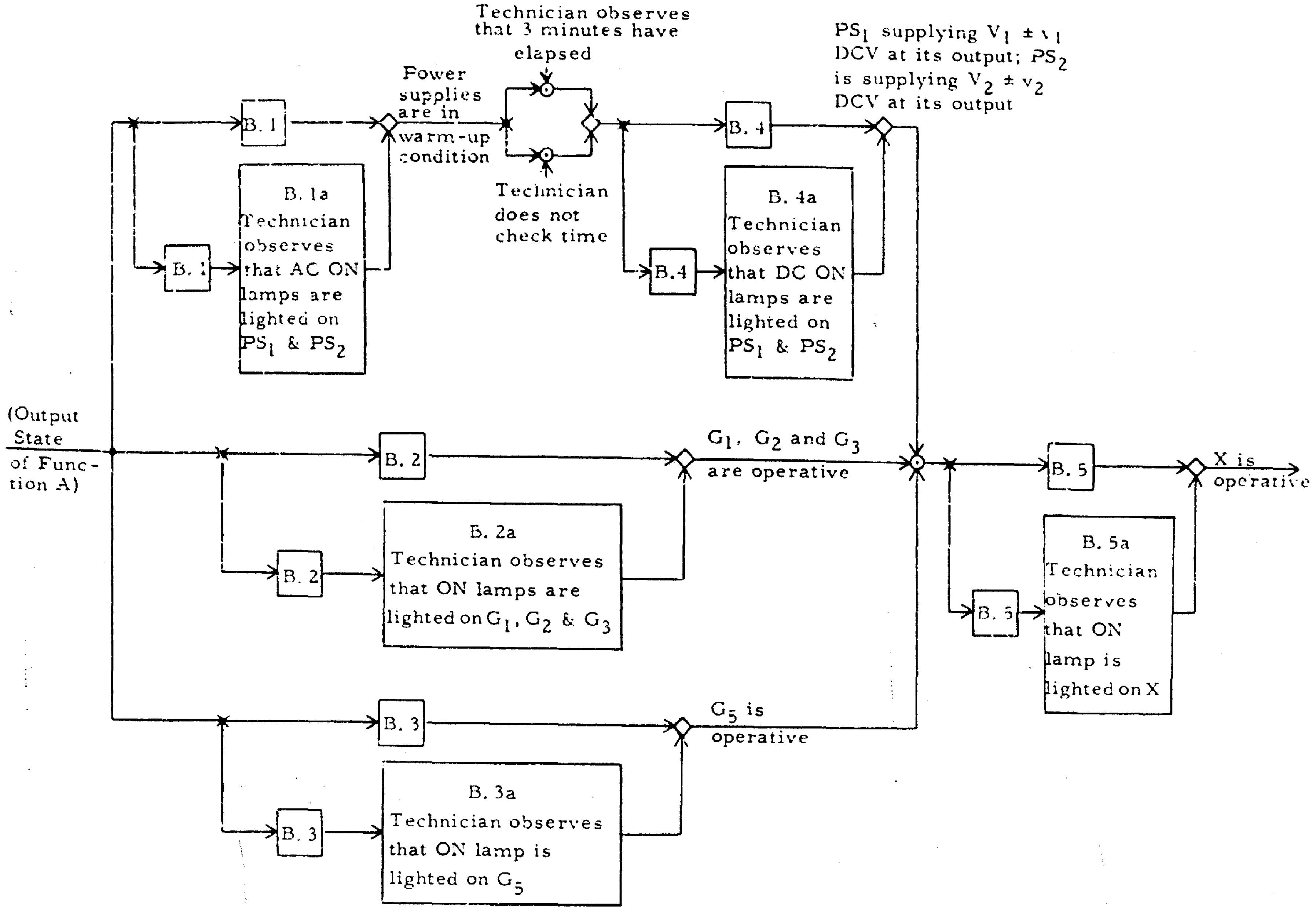


Figure III-7. GSSM of function B in example.

b. The system requires only that the equipment be operative, it does not require that lamps light. Indicator lamps serve to increase the probability that an operative state will be reached, but they are not essential to system performance.

c. Power supplies generally will operate if the DC voltage is turned on sooner than the manufacturer recommends. However, the load on the supply may be excessive, resulting in a reduction in life and reliability.

d. Note that the comments regarding the three minute wait would not be necessary if a safety timing mechanism made it impossible to switch DC ON before three minutes had elapsed. This illustrates the need to know the system in detail.

e. It is assumed that, for this particular system, X cannot be turned ON unless B. 1, B. 2, and B. 3 are performed first. However, investigation may prove that X may be turned on at any time; if that were true, the input state for B. 5 would be identical to the input state for B. 1, B. 2 and B. 3.

6. Example Revised

Assume that the GSSM constructor cannot understand why B. 5 must occur after B. 1, B. 2, and B. 3; so he consults one of the engineers and discovers that B. 5 can only occur after the power supplies are turned on and after G. 5 is turned on, but not necessarily after G. 1, G. 2 and G. 3 are on. The GSSM for Function B would have to be correlated to look like the structure shown in Figure III-8. (Note that the verbiage is omitted in order to conserve space.)

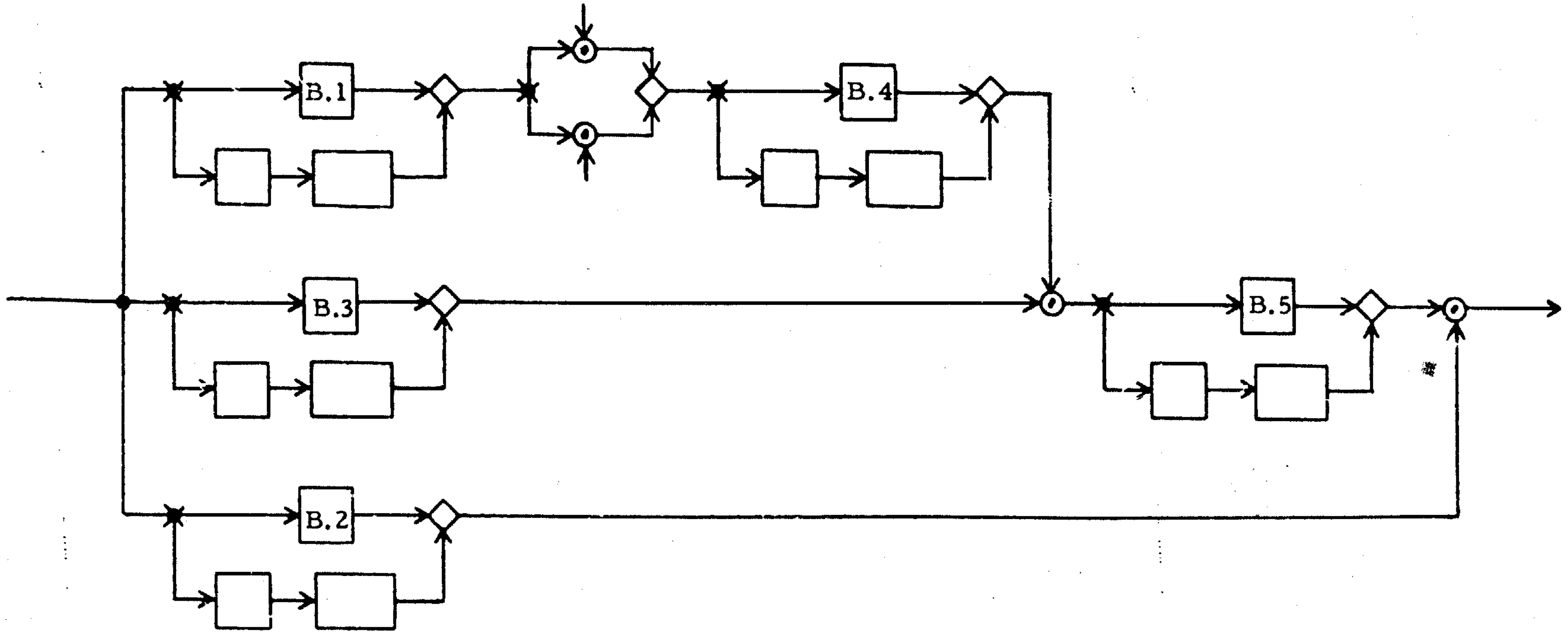
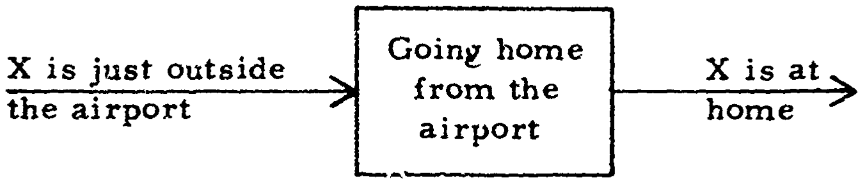


Figure III-8. A schematically represented revision of Figure III-7.

C. Construction Rules for Special Kinds of Situations

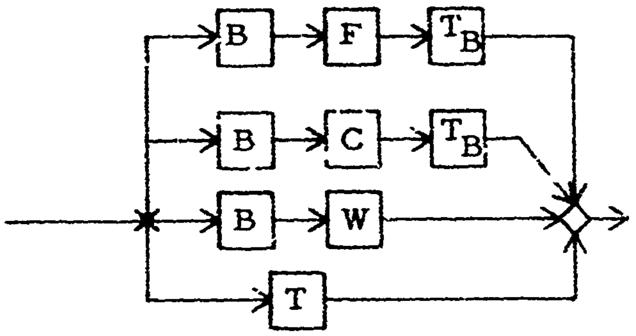
1. Alternative activities or activity sequences should begin at the common input state and end at the common output state, even if elements must be repeated.

   For example, assume the function "going home from the airport":

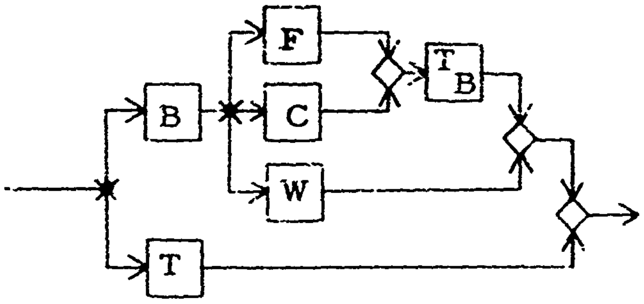


X may take a bus (B) or hail a taxi (T). If X takes a bus, he may walk home from the bus stop (W) or take a taxi (T_B). If X chooses to take a taxi from the bus stop, he may be able to find one locally available (F) or he may need to call for one via the corner telephone (C). *

The correct procedure is to follow the above rule to start and end at the same common states



Do not try to minimize the number of blocks in the diagram (even though it presents the same diagrammatic information as the correct version)



By using the correct procedure, one can analyze each total strategy independently.

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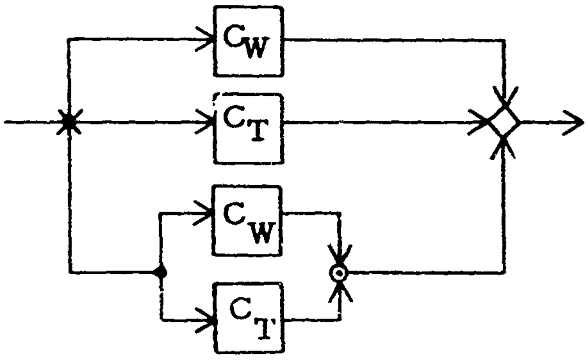
* Note: Other alternatives are conceivable, but based upon one's knowledge of the system, they are not meaningful. For an absurd example, X might conceivably find a pair of skates and skate home. For a more sane example, X could have driven a car to the bus stop and left it there until his return. However, based on our knowledge of X (or lack of parking spaces near the the bus stop) the probability is almost zero that he would use that strategy; perhaps X has never owned a car, he is too young to drive, or his wife always uses the car.

2. Where alternative activities are not exclusive, establish diagrammatic combinations which force them to be exclusive.

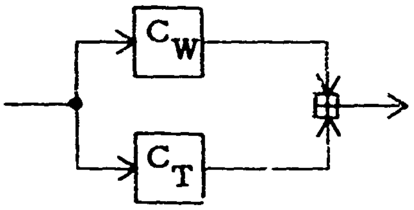
For example, assume that X told his wife (C_W) that he might call her when he arrived at the airport and that he might either call a taxi (C_T) to take him home or ask her to pick him up, depending on his feelings at the moment. Thus, X may call for a taxi or call his wife or both.

The correct procedure is to establish exclusive alternatives

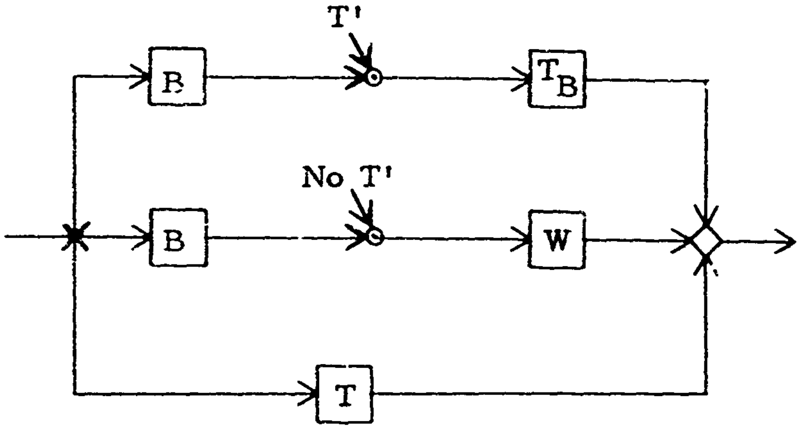


This enables independent analysis of the three possibilities

Do <u>not</u> try to use an and/or symbol



3. Where alternative activities depend upon other contingencies, those contingencies are summated with the existing state of the system. For example, in the example under 1 above, assume that if a taxi is available (T') when X gets off the bus, he will take it, otherwise he will walk.

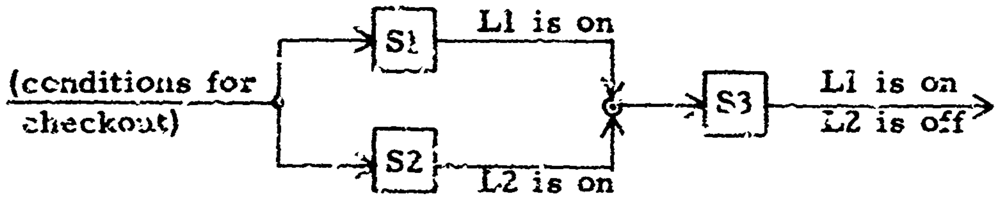


4. Always avoid redundant paths[*].

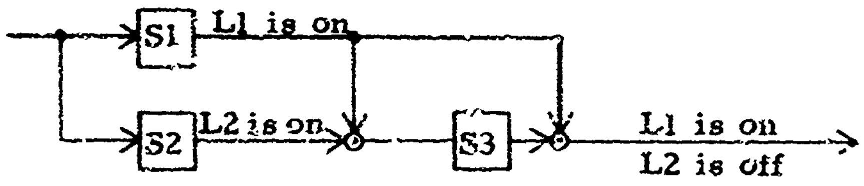
Example 1:

Assume an operator has three checkout switches to operate. S1 turns on one light, L1, and S2 turns on L2. Subsequently, S3 turns off L2 and leaves L1 on.

The correct diagram gives all necessary information



Do not indicate a continuation that is already specified by the diagram

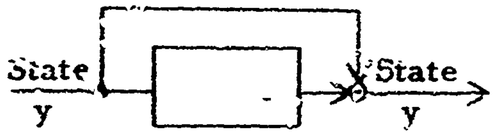


Example 2:

If an activity is required (e.g., for checkout) and it is essential that the activity does not change the state of the system, do not add additional paths; the state description indicates the requirement.

Correct

Wrong



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[*] The example which was carried through the previous three rules cannot readily be used to illustrate this rule. Thus, it is to be noted that every rule may not be applicable to all systems; every system must be approached uniquely.

IV. CONSTRUCTING THE MATHEMATICAL STATE SEQUENCE MODEL (MSSM)

A. Introduction

The MSSM is one or a set of equations which express the relation between the probability of achieving the system output state and the probabilities of accomplishing the PEF Units which the system comprises. The information for the mathematical model comes directly from the completed GSSM, so it is assumed that the graphic model is complete and accurate before the steps in this section are taken.

Constructing the MSSM is relatively easy once the basic rules are understood. At this time, it is uncertain whether that simplicity reflects the present youthful stage of development of the technique or is an inherent characteristic of the technique; the latter seems more likely.

Step-by-step instructions for constructing the mathematical model will be presented. An example will illustrate each step; the symbols shown in Figure III-1 will be the keys to establishing the correct relations among the components of the model. In addition, some mathematical symbols defined in Figure IV-1 will also be used.

B. Basic Principles

All Mathematical State Sequence Models are expressions equating the probability of an output state to the determining probabilities. The fundamental principles of MSSM construction depend upon connecting symbols, as follows:

Rule 1: The probability of the output state of a required set of PEF Units is related to the product of the probabilities associated with those PEF Units.

The first rule applies to:

a. A series of any number of PEF Units with no connecting symbols between them (See No. 1 in Figure III-2), and

b. Any arrangement of PEF Units connected only by DOT and AND symbols (See Nos. 2 and 3 in Figure III-2).

The mathematical expression for all such arrangements is

Symbol	Meaning	Example
$P(\ )$	The probability of whatever is contained in the parentheses.	P(B.3) = the probability of the required output state of element 3 of Function B. (It is assumed that the input state to B.3 initiated that elemental personnel/ equipment function.)
$\prod_{i=1}^{n}$	The product of the n values following the symbol.	Assuming the system has four Functions, as shown in Figure III-5, $\prod_{i=1}^{4} P(i) = \prod_{i=A}^{D} P(i) = P(A)P(B)P(C)P(D)$ That is, the symbol says "multiply the four probabilities," substituting for i all letters from A to D.
$\sum_{j=1}^{m}$	The sum of the m values following the symbol	$\sum_{j=1}^{m} X_j = X_1 + X_2 + X_3 + X_4 + X_5$ Just as for the product symbol, the summation symbol says, "substitute for j all whole numbers from 1 to m."
...	Three dots mean "and so on"	A x B x C x ... x n is the same as $\prod_{i=A}^{n} i$; often, it is simply written A x B x C x ... A + B + C + ... + m is the same as $\sum_{j=A}^{m} j$; often, this is simply written as A + B + C ...

Figure IV-1. Mathematical symbols which are used in MSSM.

$$P(\text{output}) = P(\text{in}) \prod_{i=1}^{n} P(i)$$

where P(in) is the probability of the input state, and i represents the code numbers assigned to the component PEF Units.

Thus, for No. 1 in Figure III-2, the MSSM is $P(z) = P(y)P(A)P(B)$. For Nos. 2 and 3 in Figure III-2, the models are identical, $P(z) = P(y)P(A)P(B)P(C)$.

Referring now to Figures III-7 and III-8, if no alternate procedures were possible (i.e., if all diamonds and crossed dots were eliminated) the MSSM for both GSSM constructions would be the same:

$$P(x \text{ is operative}) = P(\text{output}) = P(A_0) \prod_{i=1}^{5} P(B.i) =$$

$$P(A_0)P(B.1)P(B.2)P(B.3)P(B.4)P(B.5)$$

where $P(A_o)$ is the probability of the output state of Function A.

Rule 2: The probability of the output state of an alternative set of PEF Units is related to the weighted sum of the probabilities associated with those PEF Units.

The second rule applies to alternative approach possibilities, where the input state for two or more PEF Units stems from a CROSSED DOT (see No. 4 in Figure III-2). The general mathematical expression for that arrangement is:

$$P(\text{output}) = P(\text{in}) \sum_{j=1}^{m} K_j P(j)$$

where K_j is a constant associated with P(j), and j represents one of the alternatives.

Thus, for No. 4 of Figure III-2, the MSSM has two parts:

I. $P(a) = P(y)\,[K_{A_1} P(A_1) + K_{A_2} P(A_2) + K_{A_3} P(A_3)]$

II. $P(z) = P(a)P(B)$ according to the first rule.

To obtain the overall MSSM, the two parts are combined by substitution:

$$P(a) = P(B)P(y)\left[\sum_{j=1}^{3} K_{A_j} P(A_j)\right]$$

It may be noted that it is always true that $\sum_{j=1}^{m} K_j = 1.0$ for any set of alternative approaches.

<u>Rule 3</u>: The sum of the probabilities of alternative output states of a PEF Unit is directly related to the total probability of the output state for that PEF Unit.

The third rule applies to alternative <u>output states</u> and generally occurs less frequently than the first two. The general mathematical expression for that arrangement is:

$$\sum_{j=1}^{m} P(j) = P(in) \sum_{j=1}^{m} P(L_j)$$

where L is the PEF Unit whose output is split by an EXCLUSIVE OR connecting symbol.

For example, assume that a computer must be fed a complex problem for which three different unpredictable answers (or range of values) are possible; this rule applies if each possible answer must be followed by a different procedure each of which leads ultimately to the system output state. This situation is diagrammed in Figure IV-2.

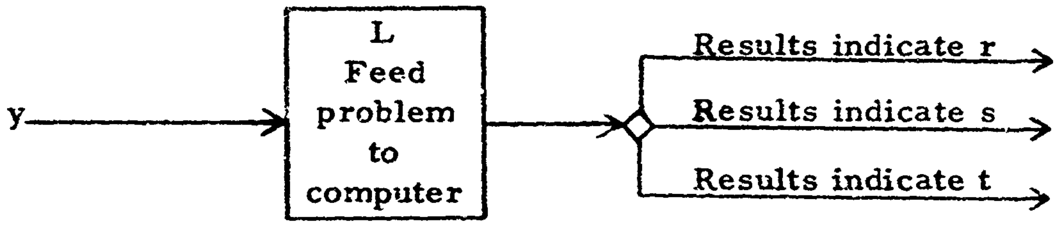


Figure IV-2. Hypothetical example of an OR output

The MSSM for Figure IV-2 is:

$$P(r) + P(s) + P(t) = P(y)\,[P(L_r) + P(L_s) + P(L_t)]$$

where, for example, $P(L_r)$ is the probability that output state r will follow after L occurs.

C. Procedural Steps

It will be necessary to write equations for portions of the GSSM at a time. Therefore, to aid construction of the MSSM, it will be helpful to assign reference symbols to certain states of the system. To do this, it may be helpful to construct a skeletal GSSM as illustrated in Figure IV-3.

Step 1

Using lower case letters, assign a different reference letter at the following locations in the GSSM:

a. Just before a CROSSED DOT,

b. Just after a diamond, i. e., EXCLUSIVE OR. (This overlaps with the next two steps.)

c. If a diamond is associated with a previous CROSSED DOT, assign the same letter, but with different numerical subscripts, to all lines leading into the diamond, and assign that same letter without a subscript to the line going out from the diamond. (See output of Function A in Figure IV-3.)

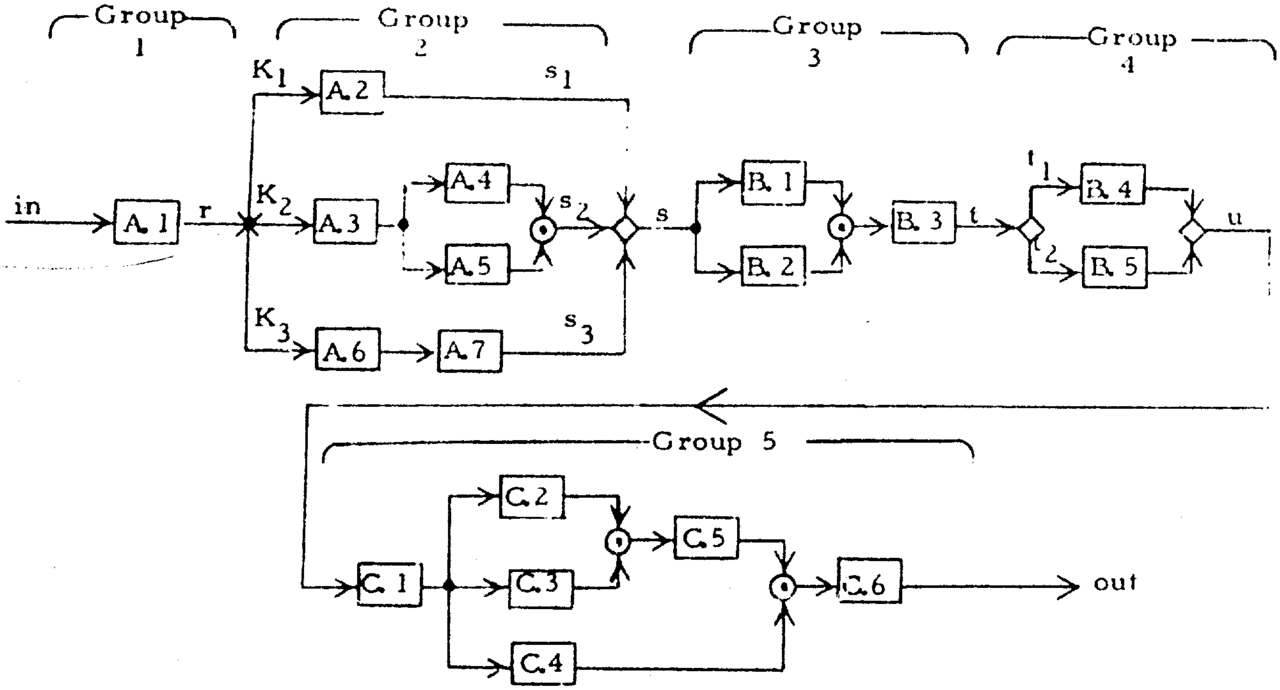
d. If a diamond appears at the output of a PEF Unit, assign the same letter, but with different numerical subscripts to all lines leading away from the diamond, and assign the same letter without a subscript to the line going into the diamond. (See elements B. 3, B. 4, and B. 5 in Figure IV-3.)

Step 2

Starting at the beginning of the GSSM, apply the appropriate rule between every sequential pair of reference letters. If the reference letters have subscripts, observe whether Rule 2 or Rule 3 is to be applied, then proceed as follows:

a. If Rule 2 applies, write equations relating each subscript reference letter to the preceding reference letter, (i. e., to the state of the system just before the CROSSED DOT). Then write the symbolic form of the following equation: Probability of the reference letter having no subscript equals the sum of the probabilities of each of the same reference letters with subscripts.

b. If Rule 3 applies, write equations relating each subscripted reference letter to the next subsequent reference letter(s).



1. $P(r) = P(in)P(A.1) = P(A.1)$ See Note No. 1
2. $P(s_1) = K_1P(r)P(A.2)$ See Note No. 2
3. $P(s_2) = K_2P(r)P(A.3)P(A.4)P(A.5) = K_2P(r) \prod_{i=3}^{5} P(A.i)$
4. $P(s_3) = K_3P(r)P(A.6)P(A.7)$
5. $P(s) = P(s_1) + P(s_2) + P(s_3)$

   $= P(r) [K_1P(A.2) + K_2p(A.3)P(A.4)P(A.5) + K_3P(A.6)P(A.7)]$
6. $P(t) = P(s)P(B.1)P(B.2)P(B.3)$
7. $P(t) = P(t_1) + P(t_2)$ See Note No. 3
8. $P(n) = P(t_1)P(B.4) + P(t_2)P(B.5)$
9. $P(out) = P(u)P(C.1)P(C.2)P(C.3)P(C.4)P(C.5)P(C.6) = P(u) \prod_{i=1}^{6} P(C.i)$

Substituting then, and assuming that $P(t_1) = P(t_2) = 1/2\ P(t)$,

$$P(out) = 1/2\ P(t)\ [P(B.4) + P(B.5)] \prod_{i=1}^{6} P(C.i)$$

$$P(out) = 1/2\ P(s)\ [P(B.4) + P(B.5)] [\prod_{i=1}^{6} P(C.i)] [\prod_{i=1}^{3} P(B.i)]$$

$$P(out) = 1/2\ P(A.1)\ [\sum_{j=1}^{3} P(s_j)] [\sum_{j=4}^{5} P(B.j)] [\prod_{i=1}^{6} P(C.i)] [\prod_{i=1}^{3} P(B.i)]$$

where $\sum_{j=1}^{3} P(s_j) = K_1P(A.2) + K_2P(A.3)P(A.4)P(A.5) + K_3P(A.6)P(A.7)$

Figure IV-3. A hypothetical, skeletal GSSM.

Also write the symbolic form of the following equation: Probability of the reference letter having no subscript equals the sum of the probabilities of each of the same reference letters with subscripts.

Step 3

After the entire series of equations are written for the system, start with the last equation and perform the following operation repeatedly until no reference letters appear in the equation relating P(in) to P(out), always keeping P(out) on the left side of the equation:

Substitute for P(reference letter) its equivalent value, as determined in a prior equation. For example, if

$$P(a) = P(in)P(A)$$

$$\text{and } P(out) = P(a)[K_1P(B) + K_2P(C)]$$

$$\text{then } P(out) = P(in)P(A)[K_1P(B) + K_2P(C)]$$

D. Example and Notes

The equations accompanying Figure IV-3 illustrate the application of the steps in the preceding section. Some clarifying comments will be made in the form of notes to which the equations make reference.

Note 1: It is always assumed that the probability of the input state to the total system is 1.0.

Note 2: The K values are proportionality constants, indicating the relative extent to which the associated alternative is used in comparison with the other possible alternative(s). K values are either determined by observation or they are assigned arbitrarily for analytical convenience (i.e., one might wish to investigate the difference it would make to the system if $K_1 = 1.0$ and $K_2 = K_3 = 0$, rather than if $K_2 = 1.0$ and $K_1 = K_3 = 0$, or if $K_3 = 1.0$ and $K_1 = K_2 = 0$).

Note 3: Experience or knowledge of the system should be adequate to estimate the relative occurrences of alternative outcomes of a personnel/equipment function. If no estimation is possible, assume equal likelihoods of obtaining all possible outcomes. Therefore, in the example, if no guess is better than any other, assume $P(t_1) = P(t_2) = 1/2\,P(t)$.

V. ALLOCATING PROBABILITIES

A. Introduction

This section is concerned with the procedure for allocating the probability components of the PEF Unit standards. Those are the probabilities with which the required output states -- shown on the GSSM -- must be accomplished in order for the overall system effectiveness requirements to be met.

In order to allocate probabilities of accomplishing PEF Units, one must first determine a means for specifying the relations among the PEF Units so as to be able to assign a weighting or index value to each unit according to its relative expectancy of accomplishment. To date, no means exists for deriving a reliable and meaningful index which reflects that expectancy. However, in an effort to test the technique, the "data store" developed by Payne and Altman was used to derive a probability index.[1] The figures in the "data store" were treated as if they were weighting values, rather than as actual probabilities of performance.

B. General Procedure

To describe the procedure, it will be assumed that an Index of Task Accomplishment (IOTA) is derivable for each PEF Unit. If we let $P(\ )$ = the probability of accomplishing the PEF Unit in the parentheses and $I_a(\ )$ = the IOTA for the same PEF Unit, then, in general,

$$P(\ ) = f[I_a(\ )] \qquad \text{(V-1)}$$

That is, the probability of accomplishment is a definable function of the index of accomplishment.

Step 1

Referring to the system effectiveness requirements, substitute in the MSSM the required value for P(out).

Step 2

As a result of that simple substitution, all probabilities in the MSSM become required probabilities of accomplishment, i.e., $P(\ )$ values.

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[1] Payne, D., and Altman, J. W. An Index of Electronic Equipment Operability, Pittsburgh, Pennsylvania: American Institute for Research, January 1962.

$$P(\text{out}) = f'[P(\text{PEF Units})] \qquad \text{(V-2)}$$

where f' is a different function from f in Equation V-1. Since Equation V-1 is true, then

$$P(\text{out}) = f'[f\{I_a(\text{PEF Units})\}] \qquad \text{(V-3)}$$

Therefore, substitute for each P( ) in Equation V-2 its equivalent, respective $f[I_a(\ )]$.

Step 3

Solve Equation V-3 for the values of IOTA.

Step 4

Substitute the values into Equation V-1 one at a time and compute each P( ).

C. Concluding Example

An exceedingly simple example will be used to illustrate the approach and conclude the discussion. Assume a system comprises two PEF Units in series, so that the MSSM is

$$P(\text{out}) = f'[P(\ )] = \prod_{i=A}^{B} P(i) = P(A)P(B) \qquad \text{(V-4)}$$

From the system effectiveness requirement, we find that P(out) = 0.95. Thus,

$$P(\text{out}) = 0.95 = P(A)P(B) \qquad \text{(V-5)}$$

Assume that the "data store" was used to obtain the following IOTA estimates:

$$I_a(A) = 0.87 \text{ and } I_a(B) = 0.92$$

Also, it has been hypothesized that:

$$P = f(I_a) = k(1-I_a) + I_a{}^{*} \qquad \text{(V-6)}$$

where k is constant for any given system. Substituting in Equation V-5,

$$0.95 = [k\{1-I_a(A)\} + I_a(A)]\,[k\{1-I_a(B)\} + I_a(B)]$$

$$0.95 = [k\{1-0.87\} + 0.87]\,[k\{1-0.92\} + 0.92]$$

$$0.95 = (0.13\,k + 0.87)\,(0.08\,k + 0.92)$$

$$95 = 1.04\,k^2 + 18.92\,k + 80.04$$

$$k^2 + 18.2\,k - 14.4 = 0$$

$$k = \frac{-18.2 \pm \sqrt{18.2^2 + 57.6}}{2} = -9.1 \pm 9.86 = \underline{0.76};\ -18.96$$

From Equation V-6

$$P(A) = k(1-I_a) + I_a = 0.76(0.13) + 0.87$$

$$P(A) = 0.969$$

$$P(B) = 0.76(0.08) + 0.92$$

$$P(B) = 0.981$$

Thus, in order to meet the system effectiveness requirement that P(out) = 0.95, the required probabilities of accomplishing the PEF Units must be P(A) = 0.969 and P(B) = 0.981.

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[*] Note that Equation V-6 requires $0 \leq I_a \leq 1.0$