

**A METHOD FOR PERFORMING HUMAN  
ENGINEERING ANALYSIS OF WEAPON SYSTEMS**

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## FOREWORD

This report covers part of the work performed by Stanford Research Institute under Contract No. AF 33(616)-5688, "A Method for Performing Human Engineering Analyses of Missile Systems." The contract was issued by authority of Project 8(8-7192), Task 71602. The contract was administered by the Engineering Psychology Branch of the Behavioral Sciences Division of the Aerospace Medical Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. The contract was initiated and originally monitored by Austin W. Kibler, Capt., USAF, and was later monitored by Mr. Charles Bates, Jr.

This study was conducted at Stanford Research Institute in the Systems Analysis Group of the Management Sciences Department under the administrative direction of William L. White, Assistant Director, Division of Economics Research. The author is indebted to Joel I. Cooper, Anne C. Meier, Dr. Maurice Rappaport, and K. H. Schaeffer, who participated in the over-all project, for their critical comments on this phase of the work, and to Miss T. Morita who provided assistance throughout the project.

The work was greatly aided by the continuous active support and advice of Captain Austin W. Kibler, and benefited from a critical discussion of its underlying concepts by the participants of a seminar, called for this purpose, and held at Litton Industries, Beverly Hills, California on 4-5 March 1959. The participants were: C. W. Anderson, D. W. Atkins, J. R. Donahue, Jr., C. J. Erickson, D. Greek, D. Henderson, Dr. J. E. Judge, Dr. D. Meister, Lt. Colonel W. G. O'Brien, T. Oehrlein, D. M. Platt, Dr. G. F. Rabideau, M. Rudov, J. B. Shook, Dr. C. W. Simon, P. Tobias, and Dr. H. L. Wolbers. The ideas presented here have drawn upon earlier work by Joseph Dresner (now at Space Technology Laboratories, Inglewood, California) and the author.<sup>1/</sup>

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<sup>1/</sup> J. Dresner, and A. Shapero, "Operational Analysis of a Field Support Program for a Complex Weapon System," American Rocket Society, September 1955.

## ABSTRACT

One problem that has faced those charged with responsibility for the human elements of a weapon system is the development of a method of analysis which integrates the analysis of a system's human elements with that of the over-all system analysis. This kind of analysis is required to determine how the human elements affect the over-all system and how the over-all system affects its human elements, and is essential to the development of effective weapon systems.

A weapon system analysis and integration model has been developed that includes the system's human elements and that can be employed as an aid in the analysis, synthesis, evaluation, planning, and management control of weapon systems.

## PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

*Walter F. Grether*  
WALTER F. GRETHER  
Director of Operations  
Aerospace Medical Laboratory

*Contrails*  
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Section I

## INTRODUCTION

A. Systems Approach

In recent years the military services have been faced by order of magnitude increases in the severity of the operational requirements imposed by their missions and in the complexity of the equipment and operations needed to meet these requirements. This increase in severity and complexity has been coupled with the urgent need to make this advanced equipment available in the shortest possible time. In this context, those charged with the development, production, and operation of military equipment have found the traditional methods for carrying out their responsibilities to be inadequate. Neither the time nor the funds have been available to achieve operational adequacy or to correct errors of omission by "cut and try" methods. The need for an approach that considers as an integrated whole the men, mechanisms, facilities, and operations that enter into the performance of a mission has been recognized. This approach to development, production, and operation is identified as the systems approach, and the integrated entities with which it is concerned are identified as weapon systems.

Though the need for the systems approach has been recognized by those responsible for the human elements of weapon systems, it has been difficult to adequately integrate the human elements with the rest of the weapon system. The lack of tools of systems analysis for linking men and mechanisms in an integrated analytical framework is partially responsible. Such analytical tools are needed to determine how the human elements fit into and affect the over-all system, as well as to determine how the over-all system affects its human element.

B. Models

System models as analytical tools appear to provide the greatest promise for analysis of total weapon systems. Models have always played a vital role in analytical work, and a sign of maturity in the field of systems analysis will be the development of useful models. The kinds of models employed in analysis may vary from the physical model (i.e., mock-ups and model aircraft) to a variety of abstract and symbolic models. In systems analysis a number of mathematical models, as well as computer

simulations, have been developed and used to describe the functions and performance of complex electromechanical devices. To date, the simulation models that have been made of man-machine systems have primarily been used as research tools.

At the present time no analytical model of an entire weapon system which includes equipment, men, facilities, and operations appears to be in use. Search of the technical literature, discussions with practitioners in the field, and visits to several weapon system programs have served to emphasize this lack.

## C. The Systems Analysis and Integration Model

This report describes a weapon systems model which attempts to include the diverse elements of complete weapon systems. The model is referred to as the System Analysis and Integration Model (SAIM).

SAIM is a systems model which has as its key features:

1. A generalized scheme for classifying weapon system elements including mechanisms, men, and facilities.
2. A treatment of weapon system elements that is "black-box" (input-output) in nature and that is modular (building block) in form, thereby permitting wide latitude in the combination of these elements.
3. A diagrammatic matrix format for arranging and showing interconnections between system elements.
4. Use of both qualitative and quantitative means for describing system element interactions.
5. Applicability at any system level.

## D. Uses of the Systems Analysis and Integration Model

SAIM can be employed in the analysis, synthesis, evaluation, planning, and management control of weapon systems, with special emphasis on the treatment of human factors.



As an analysis and synthesis tool, it is designed to be used in:

Analysis and synthesis of the requirements and constraints of the system.

Analysis and synthesis of the functions fulfilling the given requirements and constraints.

As an evaluation tool, it is designed to be used in:

Evaluation of operational and equipment designs that are proposed to implement the selected functions.

Evaluation of operations and equipment already developed.

Evaluation of proposed operational and equipment design changes.

As a planning tool, it is designed to be used in:

Systematic determination and organization of information required for all aspects of system development.

Systematic determination of research needed to support weapon system programs in general.

As a management control tool, it is designed to be used in:

Providing for the system and its status an overview which includes dollars and schedules as well as engineering characteristics.

SAIM can be used for these purposes at every stage of a weapon system program from inception of requirements to evaluation of performance. At the beginning of a weapon system program, SAIM can serve as a general and sophisticated check list which, by the inclusion of the results of subsequent system design decisions and implementation, is gradually transformed into a detailed paper analog of a specific system. SAIM's form of construction was selected to make it applicable to any weapon system or aspect of a weapon system. In this case, it has been tailored for use by those concerned primarily with the human factors in a missile system.

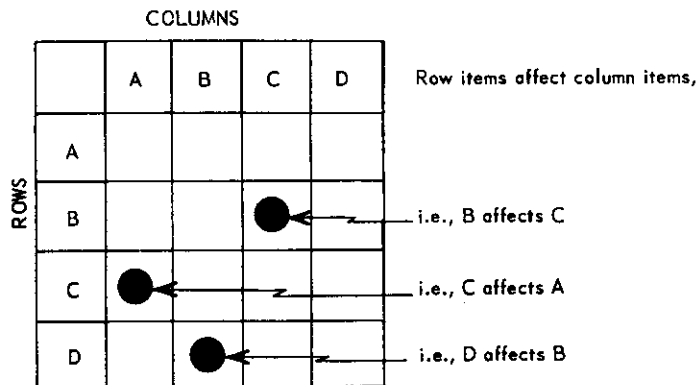
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### THE SYSTEMS ANALYSIS AND INTEGRATION MODEL

#### A. General

The Systems Analysis and Integration Model is a descriptive matrix model that classifies the elements of a weapon system into those determining the nature and form of the system, those comprising the parts of the system, and those integrating the parts of the system. In this report a suggestive detailing of this classification of system elements is provided which is applicable to missile weapon systems. This classification can be transformed for use with other weapon systems or any man-machine system. For those elements which are "parts" of the system and which are made up of mechanisms, human operations, and facilities, a means of description is used which enables the analyst to combine them into functional entities utilizing any number of such elements in building block fashion.

The elements of the system are shown in a two-dimensional square matrix which lists the system elements as headings for both the rows and the columns. The matrix squares created by the crossovers of rows and columns are used to indicate the direct connections between system elements where these connections are considered to exist. The matrix orientation is to consider the elements appearing as row headings as affecting those appearing as column headings. (See Figure 1.)



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FIG. 1  
ORIENTATION OF THE MATRIX

The matrix can be re-entered as often as practical to trace subsequent connections, thereby establishing a lattice of element connections. The direct affective connections between system elements or their attributes are described in available qualitative or quantitative terms. This can be illustrated by a relationship such as the following:

Element

Connections:      D affects  $\longrightarrow$  B affects  $\longrightarrow$  C affects A

Relationship

Expression:      (equation)  $\longrightarrow$  (stochastic)  $\longrightarrow$  (descriptive  
statement)

As a practical consideration it is not necessary for the matrix charts to contain these expressions physically. The data pertinent to an inter-element relationship may be indicated by reference.

The general classification of elements, the matrix format, and the method for describing connections are applicable at any system level, and any subsystem or component can be described in a submatrix, or in the submatrix of a submatrix. The submatrices have the same structure and organization as the matrix from which they are drawn.

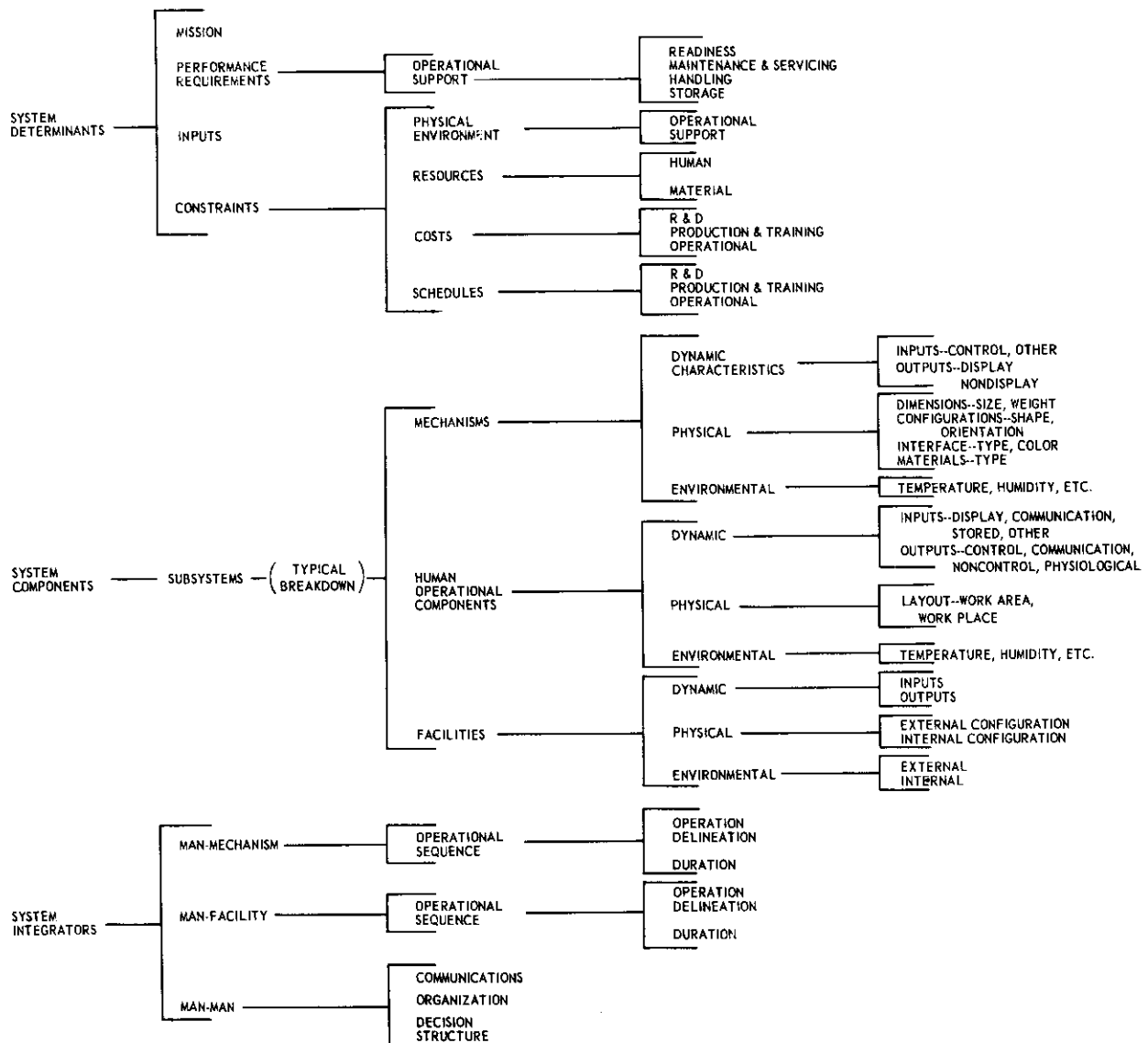
## B. System Elements and Their Classification

### 1. General

Every system is a subsystem of some larger system and is itself made up of a hierarchy of subsystems, sub-subsystems, sub-sub-subsystems, etc., each of which is a system in its own right. National defense as a system is divided into subsystems that can be selected in more than one way, e.g., by Service (Air Force, Navy, Army), or by function (defense, offense). Similarly, a Service, e.g., the Air Force, can be divided into its subsystems (SAC, ADC, ARDC, etc.) down a hierarchy of successively smaller systems until one arrives, if he chooses, at the smallest function, which is itself also a system.

The approach used in SAIM predicates that any system and any of its subsystems have the same kinds of conceptual elements, and SAIM employs a scheme for classifying these elements that is applicable to any system, on any level. (See Figure 2.)

## ELEMENTS



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**FIG. 2**  
**CLASSIFICATION OF WEAPON SYSTEM ELEMENTS**

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This method of classifying system elements is intended to:

1. Orient the user in the way in which a system and its subsystems are to be considered.
2. Provide a convenient way of linking the elements of a system with those of the system at the next hierarchal level.
3. Provide a way of linking such diverse elements as mechanisms, human operations, and facilities in one common structure.

The generalization of system elements in the classification scheme used in SAIM makes it necessary to point out that the method is meant to be used as a guide, rather than as a specific description for any particular system.

In SAIM a system's elements are divided into three general categories:

1. Elements "outside" the operating system proper which determine the nature, form, and limits of the operating system. These elements are the system determinants and include mission, performance requirements, inputs, and constraints.
2. Elements which are the system's "moving parts." These are the system components and include its subsystems, which are made up of the mechanisms, men, and facilities that are internal to and integral to the system proper.
3. Elements which act to integrate the system's "moving parts." These elements are the system integrators and include operational sequences, communications, organization, and decision structure.

At any given level, a weapon system's elements can be divided into determinants, components, and integrators. These elements can be further subdivided in a manner that meets the purposes of analysis. Ideally, all of the system elements would be described at the same level of detail; for the purposes of this report, effort has been concentrated on describing in greater detail only those elements that appear to directly affect or be directly affected by the human elements of the system. The detail employed in any specific application will vary with the system and the system level. At the over-all weapon systems level, for example, there is no need to consider the effect of a specific output from a specific console or by an individual operator. For a given system, the

analyst or designer must determine the lowest useful substratum of data for any desired level of analysis and design.

## 2. System Determinants

Weapon system determinants include those elements that are grouped under the following headings:

Mission: a general statement of the system's purpose

Performance requirements: a detailing of the purpose

Inputs from other systems

Constraints: both natural and imposed, that place bounds upon the system

This classification applies at every level of system and subsystem. For example, a mission and its expression in performance requirements can be established for a missile weapon system, for the missile itself, for the guidance subsystem, for the antenna, etc. Similarly, the constraints on a missile weapon system such as costs can be subdivided into the cost constraints of its subsystems.

### a. Mission

A general statement of the mission, together with its detailed performance requirements, sets forth the purposes of the system. "Mission" here denotes the general purpose of the weapon system as a whole. At the subsystem or component level within the system, the term "function" is used to denote the sub-mission mission. For example, an interceptor missile weapon system has the mission of intercepting manned bombers, while the function of the tracking subsystem is to track the target.

In the model, the mission statement is always framed in general terms, enabling it to remain unchanged while permitting the incorporation of changes in performance requirements as imposed by technological, budget, or other changes in the weapon system. For example, while the mission of a missile weapon system may be "the interception of manned bombers," the performance requirements may be first stated as:

bomber kill  
range--200 miles  
altitude--from 20,000 to 35,000 ft

and during development become modified to:

- bomber kill
- range--150 miles
- altitude--from 5,000 to 35,000 ft

In this example, the mission remains unchanged, while the performance requirements have been changed. A change in mission would, in the great majority of cases, mean that a new system would have to be defined.

## b. Performance Requirements

Performance requirements (often referred to as performance specifications, developmental performance specifications, general operating characteristics, military characteristics, etc.) detail the system's mission into a set of goals, objectives, and standards. These form the basis upon which a weapon system program is contracted, as well as the basis upon which the system's success is demonstrated.

In missile weapon systems, performance requirements are usually categorized into operational and support requirements. In SAIM, operational requirements are defined as those applicable to operations and equipment directly concerned with active performance of the mission. Depending on the mission, active performance can vary from a discrete one-shot event, as with a missile, to a continually performed set of activities, as with a surveillance system. Support requirements are considered to be those applicable to events and equipment concerned with preparing and maintaining the operating capability of the system elements that actively perform the mission.

There is considerable variation among missile programs as to amount and level of detail incorporated into performance requirements. This is due primarily to the varying number of decisions that have been implicitly or explicitly made as to the nature of specific hardware. Examples of the kinds of performance requirements (without preset hardware decisions) that might be imposed on a program are the following:



Operational Requirements

Kill probability  
Altitude  
Range  
Speed  
Lethality  
Maneuverability  
Vulnerability  
Response time  
Reliability  
Safety of personnel and friendly population  
Level of operational personnel used  
Geographic deployment  
Requirements derived from characteristics of associated  
equipment such as carrying aircraft

Support Requirements

Readiness

Weapon quantities: on line  
                                backup  
Warm-up conditions  
On or off launcher

Maintenance and Servicing

Type: go/no-go  
      remove and replace  
      throw-away  
Levels: at line  
         at base  
         at depot

Handling

Type of portability  
Type of mobility  
Type of transportability: air  
                                rail  
                                truck  
                                mixture

Storage

Type

Length of time

At a subsystem level, performance requirements such as "range" and "speed" would be translated into detailed performance requirements such as "thrust," "weight," "aerodynamic configuration," etc.

## c. Inputs from Other Systems

Inputs are the signals, mechanical displacements, or other forms of energy that enter or are imposed upon the system from outside its defined boundaries. An example of this at the weapon system level is the communication received by an F-104 from SAGE. At a lower system level, the input might be guidance signals received by a beam-riding missile subsystem from the radar subsystem.

## d. Constraints

Limits are imposed on the system design by the state of the art, by nature, and by the agencies that have cognizance over the system. The constraints imposed by nature or society relate to the physical environment and/or human and material resources. The constraints imposed by the cognizant agencies include those that relate to funds and developmental program time.

(1) Physical Environment. The physical environment for a missile system can be divided into two regimes that correspond with the major performance requirements categories: operational and support. For both regimes the environment can be classified in terms of such parameters as temperature, humidity, acceleration, vibration, shock, radiation, noise, ion count. However, the operational regime may be the environment at 60,000 feet encountered for 30 minutes at Mach 2, while the support regime may be a function of geographic deployment encountered for years.

(2) Resource Constraints. Resource constraints, both human and material, are imposed upon the designer by nature or by the society in which he lives. For instance, during World War II a Japanese designer could use a human as the guidance system in an expendable

Kamikaze, while the U.S. designer was deterred from such practice by his society's values. Human constraints may be quantitative, qualitative, or a combination of both. An example of the last, reflecting influences of both society and nature, would be a requirement of a military service that "no more than three Level-7 personnel will be used per missile unit."

Material resource constraints are determined by the availability of materials in nature, or specifically available to the U.S. designer--a function of society plus nature. An example of low availability in nature would be some of the rare earths. An example of low specific availability to the U.S. designer would be rubber in World War II or tungsten after the Communist capture of China. Such constraints have long been recognized by the military services and have been expressed in the assignment of material priorities or in the establishment of preferred categories of materials.

(3) Cost Constraints. No consideration of a system's constraints can be realistic without taking into account its cost and time constraints. For given performance requirements, a design for a system that has no budget or time limits will differ from a design for that system with a time limit but no budget limit, or with both budget and time limits. Cost constraints are of three categories:

- Research and Development
- Production and Training
- Operation

These three categories of cost constraint affect each other as well as the system as a whole. For example, an increase in the Research and Development and the Production costs that were incurred in making a test console a one-man operation rather than a two-man operation might be offset by a consequent decrease in operation cost.

Cost constraints can be shown to be applicable to a cost constraint category as a whole and to each element of a system individually. The dollar effect of the development of individual system elements can be determined and totaled. Changes in budgets can be entered, and the effect of the changes on the cost allowed per system element can be determined. The effects of changes in the system elements in terms of their direct costs and of their cost effects on other elements and on the system as a whole can be traced.

(4) Time Constraints. Developmental program time constraints are expressed in calendar time by dates, and these are categorized as are the dollar constraints under:

Research and Development  
Production and Training  
Operation

These constraints are treated in a manner similar to that prescribed for cost constraints--the unit here being time rather than dollars.

### 3. System Components

A weapon system's components are its subsystems. Subsystems are assemblages of mechanisms, human operations, and facilities that are defined as entities and treated as such for purposes of design, development, operation, and support. In SAIM, a subsystem is described in terms of mechanism modules, human operations modules, and facility modules. This modular treatment affords flexibility since it allows each subsystem to be handled in building block fashion, thus making it easy to describe complex functions that combine many items, and to extend or to modify the model as the system itself is extended or modified. The modules are described in simplified "black-box" terms: inputs, outputs, physical characteristics, environmental characteristics. A specific categorization of characteristics for each of the three kinds of components is employed in an extension of the building block approach. Some terms that appear as mechanism outputs also appear as human operations inputs, and similarly with human operations outputs and mechanism inputs. This redundancy is provided in order to permit separate consideration of a system element where desired.

#### a. Mechanisms

The mechanisms defined in the model are meant to represent the system level being described. For example, at one level the mechanisms represented in the model's subsystems are the missile, the ground-guidance subsystem, the launcher, and the missile tester. At a lower level, the mechanisms represented are the propulsion subsystem, the airborne guidance subsystem, and the propulsion tester. At still lower levels, the mechanisms might be on the order of scopes and amplifiers.

At any system level, the characteristics of the mechanisms are grouped under inputs, outputs, physical characteristics, and environmental

characteristics. However, since SAIM is oriented primarily toward human factors in this case, an attempt is made to tailor all pertinent descriptions of these characteristics in terms and dimensions meaningful to the human factors specialist. For convenience, when there is a choice psychological terms rather than physical terms are used to describe the characteristics of a mechanism or a facility. For example, the visual display outputs of a mechanism would be described in psychological terms using psychological units rather than physical units. (See Appendix A.)

## b. Human Operational Components

Viewing the weapon system as composed of subsystems consisting of mechanisms, men, and facilities having inputs, outputs, physical characteristics, and environmental characteristics implies the need for a way of treating the system's human and nonhuman contributions compatibly. Accordingly, in SAIM a system's human components are treated as "human operational components" that are "black boxes" of human operations. These components are not equated to men. Man is visualized as participating in the functioning of the weapon system through combinations of operational components that can vary in size from those that represent operations handled by one man in less than an hour to those that represent the efforts of many men for more than a day. More specifically, a human operational component is a combination of operations in which rigid arrangements or constraints compel events to take a certain course. The constraints of the component are intended to exclude all possibilities of action which would not be in line with the intended course; and typically the constraints cannot be altered by the action forces.

In this context, those responsible for the human factors in a man-mechanism system are responsible for designing sets of operations to be performed by men and for assuring that these operations have fixed characteristics. Steps usually taken to ensure that these operations are reproduced within given tolerances and with given reliability are:

1. Design and allocation of systems functions to be performed by man.
2. Design of work area, work place, and work environment in order to minimize variability.
3. Establishment of fixed operational procedures.
4. Training of personnel in these procedures.

5. Performance of research to provide data and methods for the better accomplishment of 1, 2, 3, and 4 above.

As with mechanisms, the human operational components defined in the model are typical of the system level being discussed, and may be a mission segment, a function, a task, or a job element. At one level, for example, it may be the operation of a tracking console. At another level, it may be a monitoring operation or a simple job of assembly. At every level, as with mechanisms, the characteristics of the human operational components are described in terms of their inputs, outputs, physical characteristics, and environmental characteristics.

(1) Inputs: The inputs to the human operations component are classified as display inputs, communication inputs, stored inputs, and other. Stored inputs are considered to be those that are learned (training, experience) and innate ability (psychological and physiological).

(2) Outputs: The outputs of the human operational component are classified in terms of information outputs, non-information outputs, and physiological outputs.

(3) Physical Characteristics: The physical characteristics of the human operational component describe the work space in which the human performs the required operations. Work space is categorized into work area layout (which treats of over-all spatial relationships of operations, operators, mechanisms, and facilities) and work place layout (which treats of those spatial relationships that concern specific subdivisions of the work area layout).

(4) Environmental Characteristics: The environmental characteristics are primarily concerned with description of the immediate environment of the work area or the place and are stated in such terms as humidity and temperature.

## c. Facilities

A subsystem's facility components are those physical structures and installations which are used for housing and supporting the mechanisms and operations of the weapon system. For example, at one level they

include buildings, and at another level, enclosures. The component characteristics of the facility are described as:

Inputs

Outputs

Physical Characteristics

External configuration

Internal configuration

Environmental Characteristics

External

Internal

#### 4. System Integrators

The system integrators are the elements that link the system's components in a "nonhardware" or abstract way. They are categorized as man-mechanism, man-facility, and man-man integrators.

##### a. Man-Mechanism and Man-Facility Integrators

Operations integrate human and mechanism components in time. For example, an operational sequence may consist of a man going to a chair, sitting down on it, picking up a phone from a desk, and dialing a number. In this instance, a number of isolated objects--man, chair, phone, and desk--are integrated by an operational sequence in time. In similar fashion man-facility integration can be described.

In SAIM the operations are described at a level consistent with that of the components appearing in the matrix. At the over-all weapon system level, where the components are launch subsystem, missile subsystem, etc., the operations described are larger, more inclusive entities such as "launch operations," or "control operations." At the subsystem level where the subsystem may be "acquisition and control," a component might be "tracker," while the operations would be "acquire," "identify," and "track."

The operational sequence requires in each case that the operations be delineated descriptively and in terms of time. The time terms include duration, start time (from some given zero point), and finish time.

## b. Man-Man Integrators

The integration of human component to human component is described in many ways. Among the integrative elements that can be employed are communications, organization, and decision structure.

Further developmental effort is being applied to this particular aspect of SAIM in an attempt to incorporate and classify communications, decision, and organization terms.

## C. Structure of the Model

### 1. Matrix Format

A diagrammatic matrix is used as the structural form in which the model is cast. The matrix can be described as a two-dimensional square matrix. The headings of the rows and columns of the matrix are symmetrical and consist of the system elements. The orientation of the matrix is such that the elements appearing as headings of rows are considered as affecting those appearing as headings of columns. The matrix is illustrated in Figures 3, 4, 5, 6, and 7, in which the elements of the matrix such as the determinants, components, and integrators are each shown in their separate forms and then in combination in the full matrix form.

### 2. Subsystem Matrices

The system components (subsystems) are represented by matrices in the same way as is the system. Their determinants, components, and integrators are defined similarly to those of the over-all system. The definition of an over-all system element provides an "envelope" in which the same element class of the subsystem must fall. For example, one of the system constraints will be a cost constraint. All of the subsystem cost constraints added together must fall within this over-all cost constraint. Another example is that of an over-all system performance requirement such as "response time," which may be 15 minutes from receipt of signal to launch of first missile. For a subsystem such as a launch



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RB-2568-2

**FIG. 3**  
**SYSTEM DETERMINANTS IN THE MATRIX**

SYSTEM COMPONENTS			SYSTEM COMPONENTS											
TYPICAL SUBSYSTEM			TYPICAL SUBSYSTEM											
			MECHANISMS			HUMAN OPERATIONAL COMPONENTS			FACILITIES					
			DYNAMIC CHARAC.	PHYSICAL CHARAC.	ENVIR. CHARAC.	DYNAMIC CHARAC.	PHYSICAL CHARAC.	ENVIR. CHARAC.	DYNAMIC CHARAC.	PHYSICAL CHARAC.	ENVIR. CHARAC.			
SYSTEM COMPONENTS	TYPICAL SUBSYSTEM	MECHANISMS	DYNAMIC CHARAC.	INPUTS		INPUTS			INPUTS			INPUTS		
				OUTPUTS		OUTPUTS			OUTPUTS			OUTPUTS		
			PHYSICAL CHARAC.	DIMENSIONS		WORK AREA LAYOUT			EXTERNAL CONFIG.			EXTERNAL CONFIG.		
				CONFIGURATION		WORK PLACE LAYOUT			INTERNAL CONFIG.			INTERNAL CONFIG.		
				INTERFACE					EXTERNAL			EXTERNAL		
		MATERIALS			TEMP., HUMIDITY, ETC.			INTERNAL			INTERNAL			
			TEMP., HUMIDITY, ETC.											
		HUMAN OPERATIONAL COMPONENTS	DYNAMIC CHARAC.	INPUTS		INPUTS			INPUTS			INPUTS		
				OUTPUTS		OUTPUTS			OUTPUTS			OUTPUTS		
			PHYSICAL CHARAC.	WORK AREA LAYOUT		WORK AREA LAYOUT			EXTERNAL CONFIG.			EXTERNAL CONFIG.		
				WORK PLACE LAYOUT		WORK PLACE LAYOUT			INTERNAL CONFIG.			INTERNAL CONFIG.		
		FACILITIES	ENVIR. CHARAC.	TEMP., HUMIDITY, ETC.		TEMP., HUMIDITY, ETC.			EXTERNAL			EXTERNAL		
				TEMP., HUMIDITY, ETC.		TEMP., HUMIDITY, ETC.			INTERNAL			INTERNAL		
DYNAMIC CHARAC.	INPUTS			INPUTS			INPUTS			INPUTS				
	OUTPUTS			OUTPUTS			OUTPUTS			OUTPUTS				
PHYSICAL CHARAC.	EXTERNAL CONFIG.		EXTERNAL CONFIG.			EXTERNAL CONFIG.			EXTERNAL CONFIG.					
	INTERNAL CONFIG.		INTERNAL CONFIG.			INTERNAL CONFIG.			INTERNAL CONFIG.					
ENVIR. CHARAC.	EXTERNAL		EXTERNAL			EXTERNAL			EXTERNAL					
	INTERNAL		INTERNAL			INTERNAL			INTERNAL					

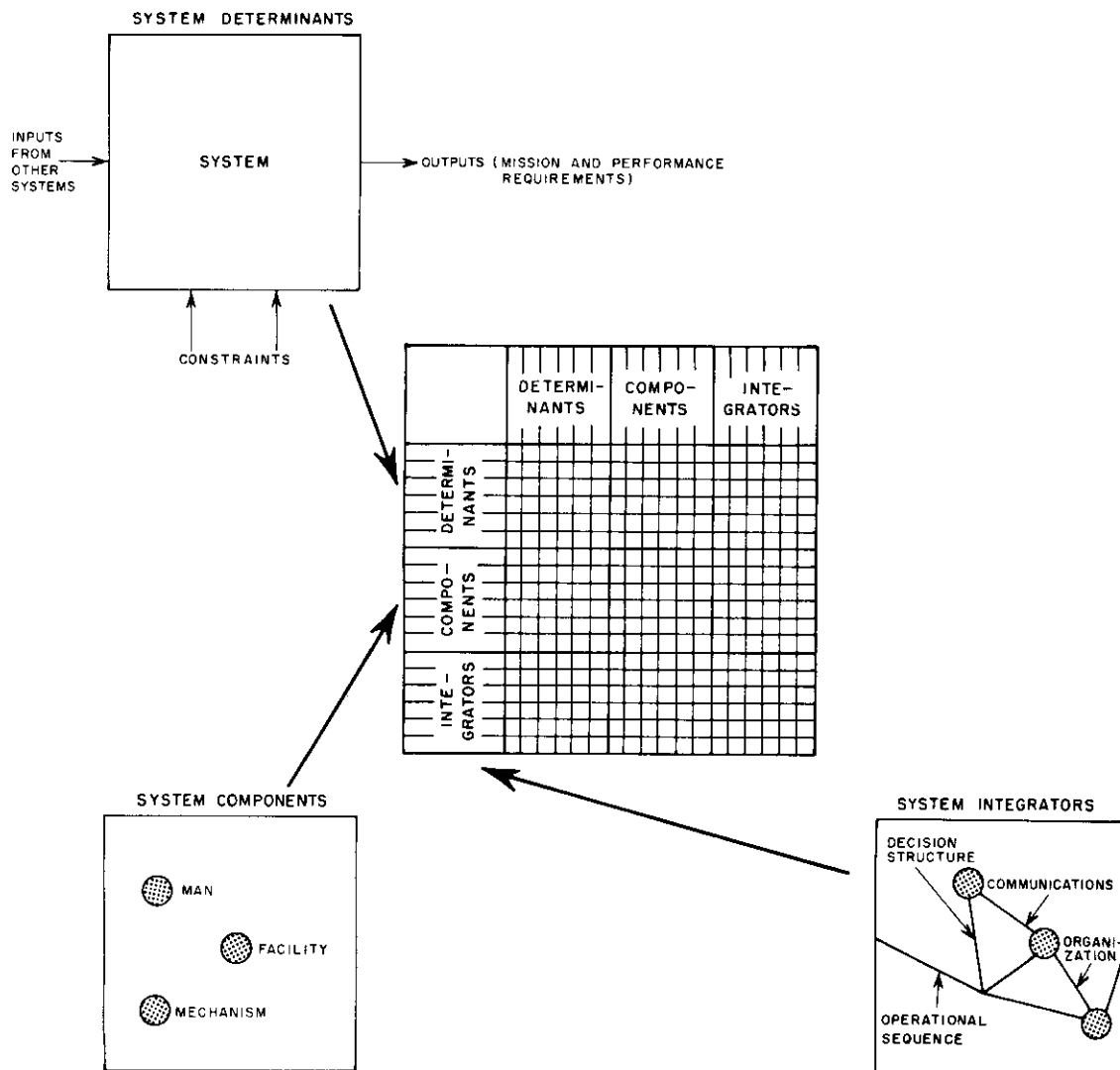
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**FIG. 4**  
**SYSTEM COMPONENTS (SUBSYSTEMS) IN THE MATRIX**

				SYSTEM INTEGRATORS				
				MAN-MECHANISM AND MAN-FACILITY		MAN-MAN		
				OPERATIONAL SEQUENCE		COMMUNICATIONS	ORGANIZATION	DECISION STRUCTURE
				OPERATION DELINEATION	DURATION			
SYSTEM INTEGRATORS	MAN-MECHANISM AND MAN-FACILITY	OPERATIONAL SEQUENCE	OPERATION DELINEATION					
			DURATION					
	MAN-MAN	COMMUNICATIONS						
		ORGANIZATION						
		DECISION STRUCTURE						

RB-2568-4

FIG. 5  
SYSTEM INTEGRATORS IN THE MATRIX



RC-2568-5

FIG. 6  
FORMAT OF SAIM

**FIG. 7**  
**SAIM MATRIX**

[illegible]

*Contrails*

console, the response time from receipt of signal to completion of its portion of the launch operation might be only 5 minutes.

The subsystem matrix is abstracted as a unit from the next higher matrix which, in effect, sets the determinants of the subsystem. The relationship of subsystem matrix to system matrix is illustrated in Figure 8.

#### D. Interaction of System Elements

##### 1. The Direct Connection

All elements of the weapon system eventually affect all other elements of the system, and a major difficulty encountered in working with systems is that of dealing with the many direct and indirect relationships of the system's elements. Practical experience with weapon systems teaches the analyst and designer to realize that a small change in one element may have a profound effect on other elements that is not readily anticipated, e.g., a small change in element A may cause a small change in element B, which may in turn have a profound effect on element C. The approach used in SAIM is to limit description of the interaction between any two elements to the direct connection between them.

The operational definition for a direct connection is "an affective connection between two elements that does not go through a third system element as defined in the matrix." For example:

A light on a console goes on (mechanism output) and affects an operator to push one of three buttons on the console (human operations component output).

In terms of the elements as classified in SAIM, this cannot be a direct connection since a third system element is involved between the light going on and the button being pushed. The direct connections in this case would be:

Mechanism output (light goes on) directly connects with human inputs (detection, distinguishability, interpretation) which directly connects with human output (button is pushed).

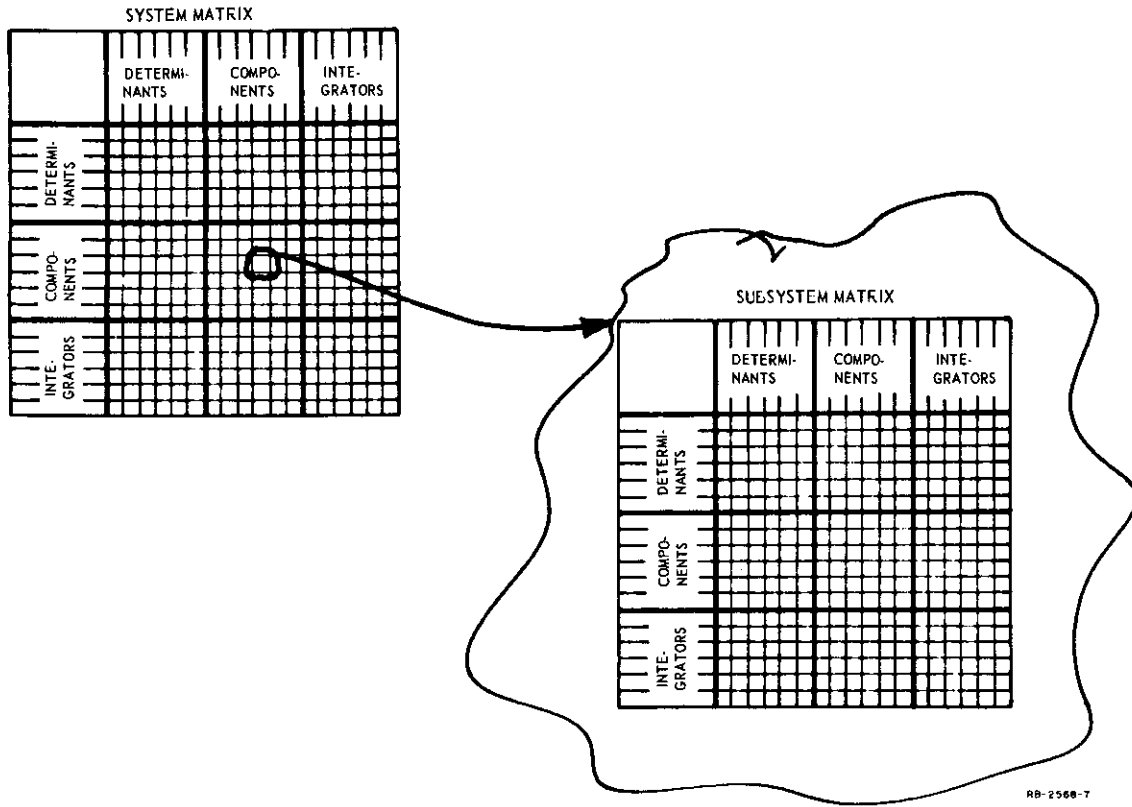


FIG. 8  
RELATIONSHIP OF SUBSYSTEM MATRIX TO SYSTEM MATRIX



## 2. System Interrelationships

Interactions of elements in SAIM are indicated in the matrix in the squares where rows cross over columns. (See Figure 9.) The simple convention employed for showing direct connections is illustrated in Figure 10.

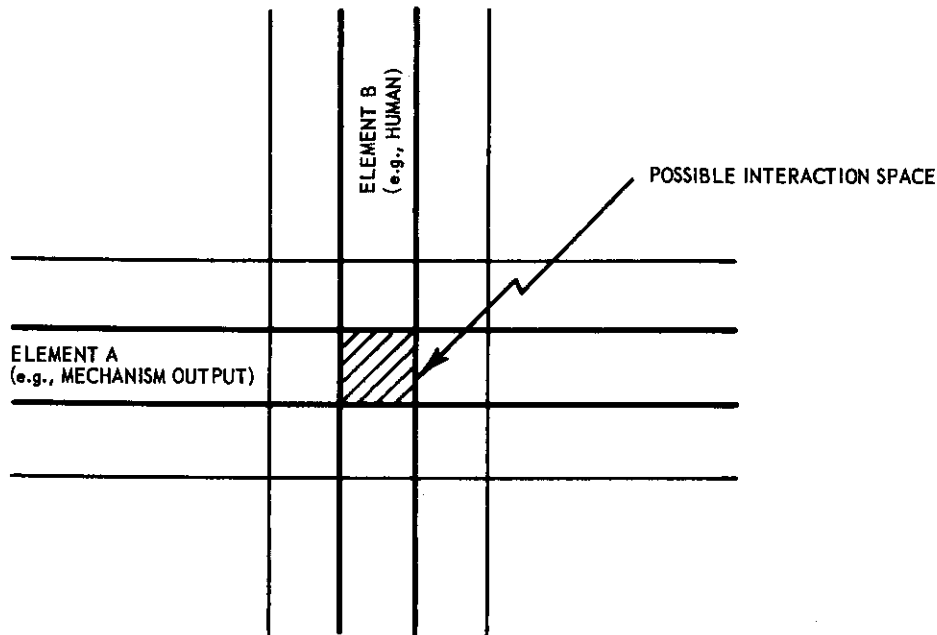


FIG. 9  
SPACE WHERE AN INTERACTION MAY BE INDICATED

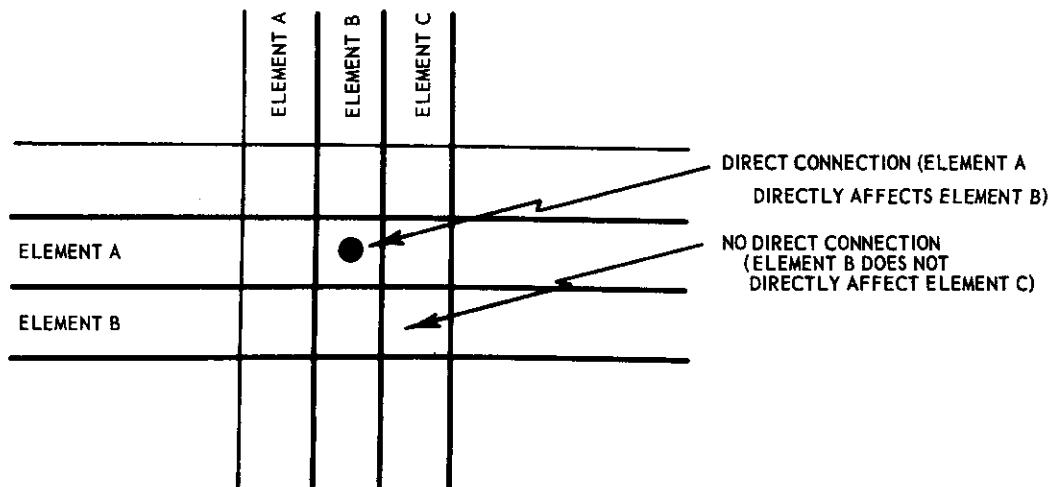
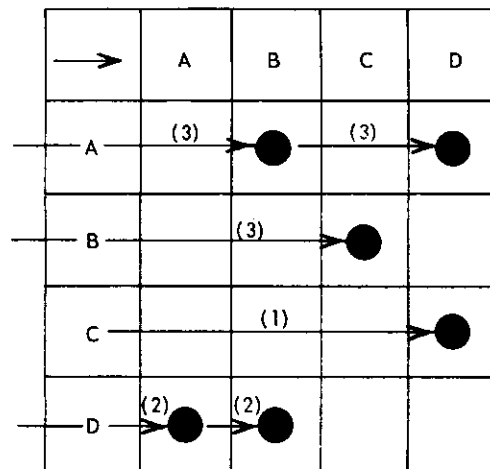


FIG. 10  
INDICATING INTERACTIONS

### 3. The Indirect, or Secondary and Tertiary Relationships

Once the primary connections have been identified, subsequent (secondary, tertiary, and further connections) can be identified by re-entering the matrix. (See Figure 11.)



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FIG. 11

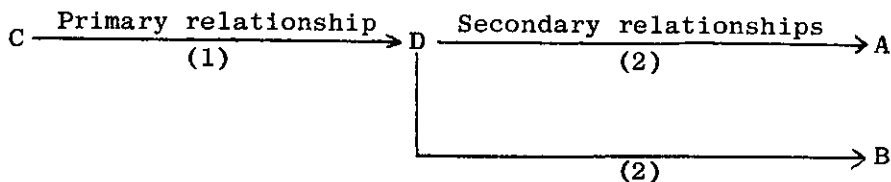
#### RE-ENTERING THE MATRIX TO ESTABLISH SECONDARY AND TERTIARY RELATIONSHIPS

If the analyst is concerned with the effects of element C on the system, he enters the matrix at C in the figure and notes that:

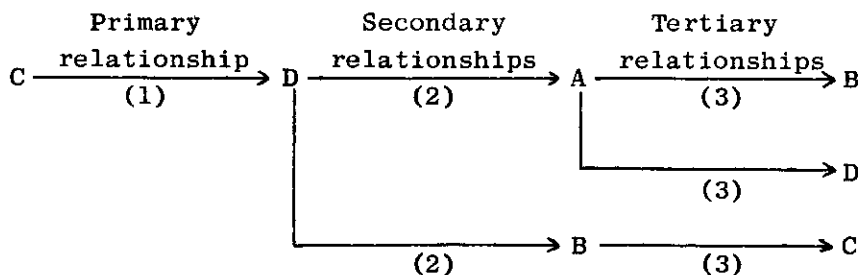
Element C directly affects element D (e.g., Facility Configuration affects Work Area Configuration). This is a primary relationship as indicated by the number (1) in the figure.

Re-entering the matrix from the left, the analyst traces the subsequent relationships of this primary relationship and notes that:

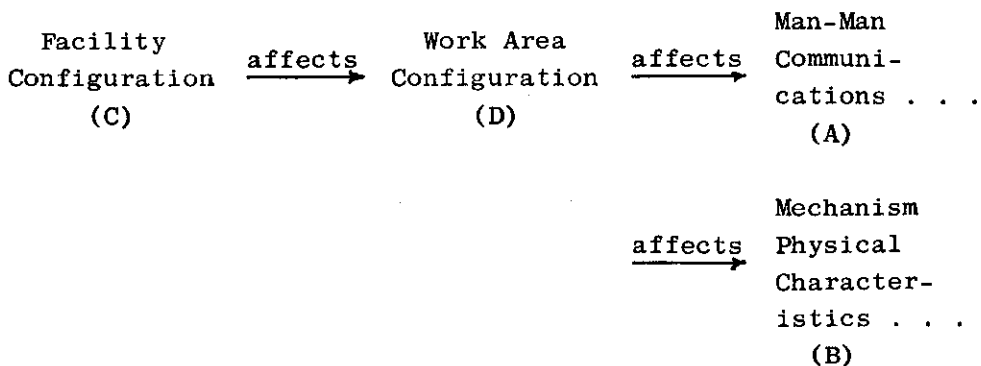
D affects A and B (e.g., Work Area Configuration affects Man-Man Communications and Mechanism Physical Characteristics). These secondary relationships are indicated by the number (2). The pattern can be shown diagrammatically in this way:



Further relationships are observed by re-entering the matrix a second time. The tertiary relationships can then be added to the pattern:

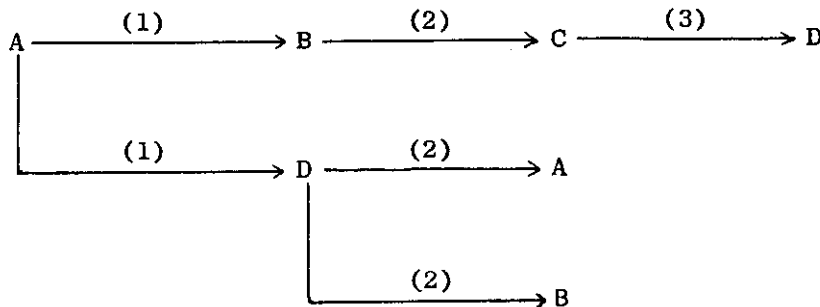


For example:



# Contrails

Whether a relationship is primary, secondary, tertiary, etc. depends on what the analyst is concerned with. In the example cited, it is a manipulation of element C (Facility Configuration). If it is instead a manipulation of element A (Man-Man Communications), the connections of A would become primary, and the pattern would be as follows:



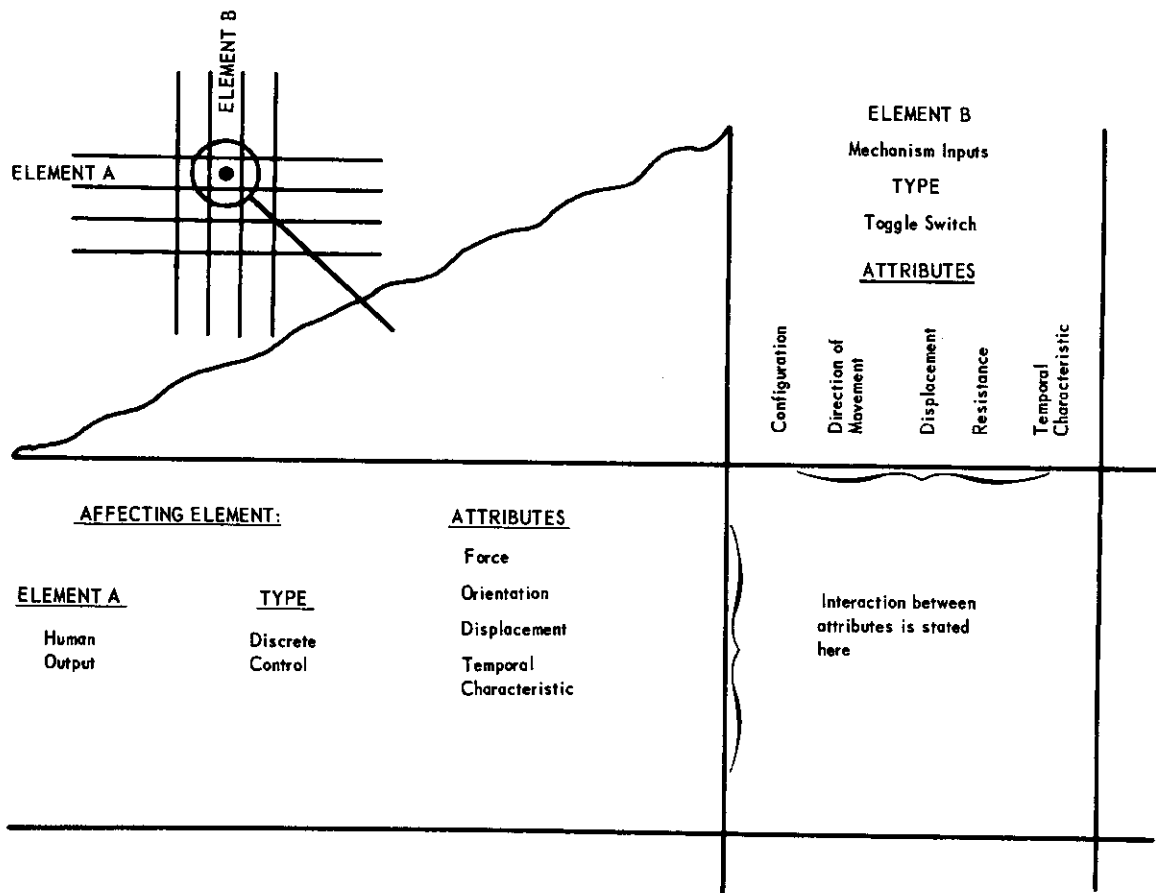
The matrix can be re-entered as often as required, but experience has shown that usually one or two re-entries are sufficient.

#### 4. Describing the Interactions between System Elements

In constructing the system matrix it is necessary first to review the element interaction spaces and to determine which elements have direct connections with each other and which do not. (In practice, however, a third category appears: those which are not immediately determined and which require further study.) Once these are identified, the main effort of the construction of the model is to determine the interactions between these elements.

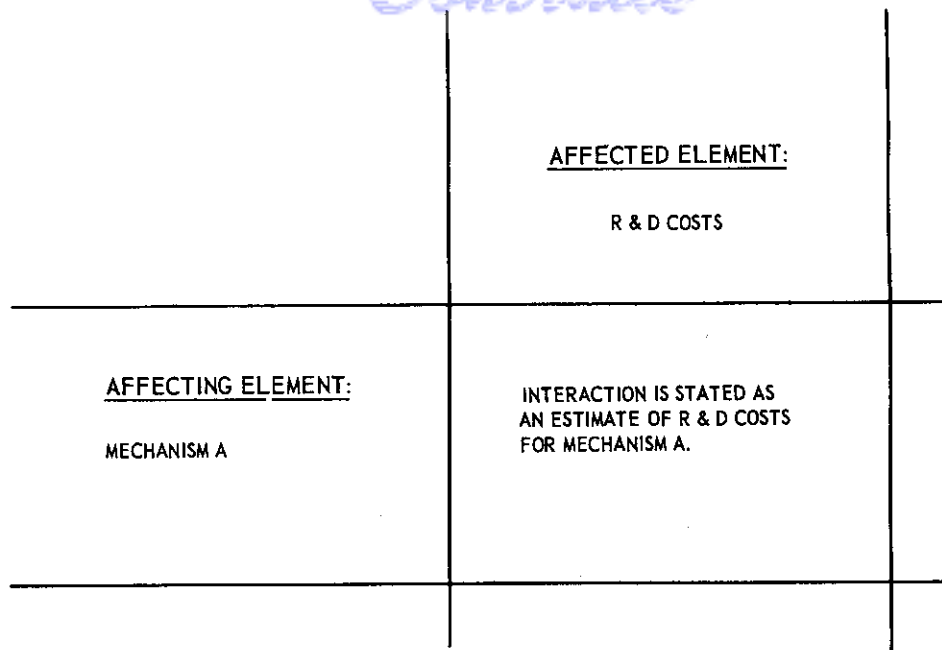
The information that is available on the interactions between the many kinds of weapon system elements appears in many forms and with various degrees of precision. The forms in which the information appear vary from experimental data expressed through mathematical equations to judgments based on experience and expressed through descriptive statements. The system model is intended to employ descriptions of element interactions in whatever form they are available, whether quantitative or qualitative.

Examples of the interactions between system elements are shown in Figures 12, 13, and 14.



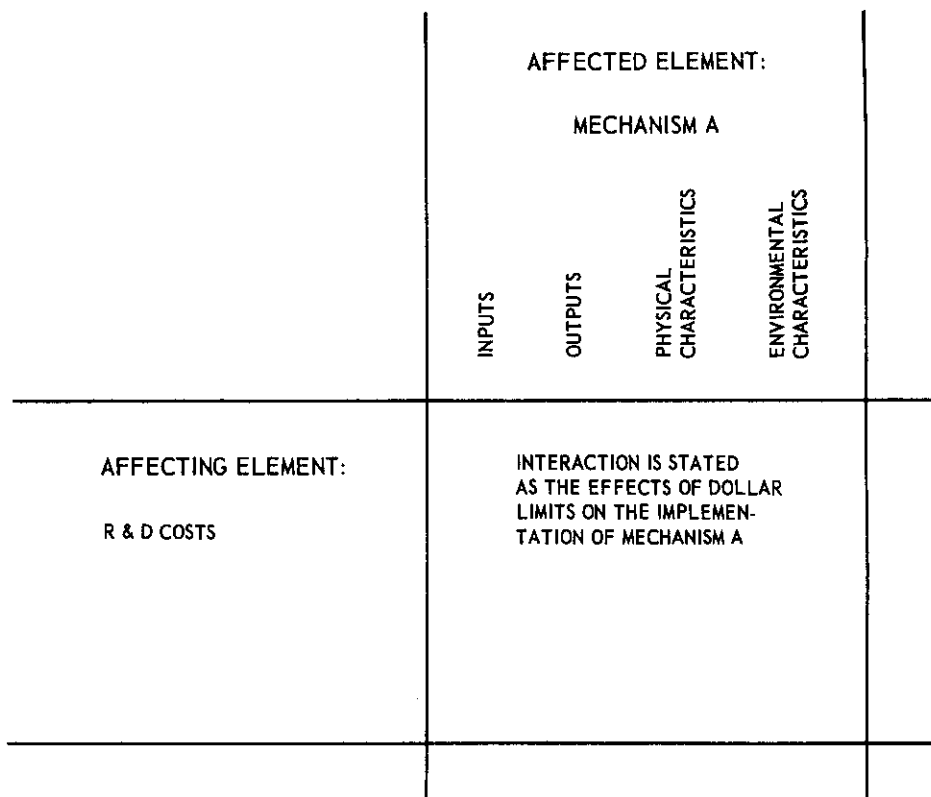
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**FIG. 12**  
**EXAMPLE OF A HUMAN OUTPUT DIRECTLY AFFECTING A MECHANISM INPUT**



RA-2568-11

FIG. 13  
EXAMPLE OF A MECHANISM DIRECTLY AFFECTING A COST CONSTRAINT



RA-2568-12

FIG. 14  
EXAMPLE OF A COST CONSTRAINT DIRECTLY AFFECTING A MECHANISM

As the development of a system progresses and the number of design decisions increases, the descriptions of a system's elements become more explicit. Consequently, the descriptions of the interactions between the system's elements become similarly explicit. Each interaction space in the matrix can be considered to be a file folder (or a reference to a file folder) within which is located the information pertaining to the direct relationship between two elements. At the early stage of design this may be all of the available information that could apply to the interaction of two elements that are defined in general terms. At a later stage, when the elements are specifically defined, the information may be a simple, precise numerical equation. An example of this type of transformation is given below.

1. It is decided to have an operator receive information from a console.

		<u>Affected Element:</u>
		Human Input
<u>Affecting Element:</u>		
Machine Output	Type:  Display (All kinds are available at this point: visual audio, tactile, proprioceptive)	Data concerned with all types of information display, and the bearing they have on such factors as detectability, distinguishability, and interpretability

# Contrails

2. It is next decided that the information will be presented visually.

		<u>Affected Element:</u>  Human Input
<u>Affecting Element:</u>  Machine Output	Type:  Display: Visual Label Indicator Light Scope	Data concerned with all types of visual display and their effect on human input attributes are pertinent

3. It is next decided that the visual display will be a light.

		<u>Affected Element:</u>  Human Input
<u>Affecting Element:</u>  Machine Output	Type:  Display Visual Light	Data concerned with all kinds of lights and their effect on human input attributes are pertinent here



4. Light display is completely specified.

		Affected Element:	
		Human Input	
		Display	Innate Ability
		Stored	Learned
Affecting Element:			
Machine Output	Type:	Specific relationship of specific output attributes to human input attributes	
	Display		
	Visual		
	Specific Light		
	Color		
	Brightness		
	Contrast		
	Configuration		
	Temporal		

E. The Model and Time

1. General

a. The model is concerned with time in two ways:

- (1) In terms of the changes to the system, and consequently the models that result from the developmental process. Here time is calendar time and the question is one of updating the matrix.

- (2) In terms of the operations that occur during the performance of the system's mission. Here time is clock time and the question is one of taking into account operational time in the structure of the model.

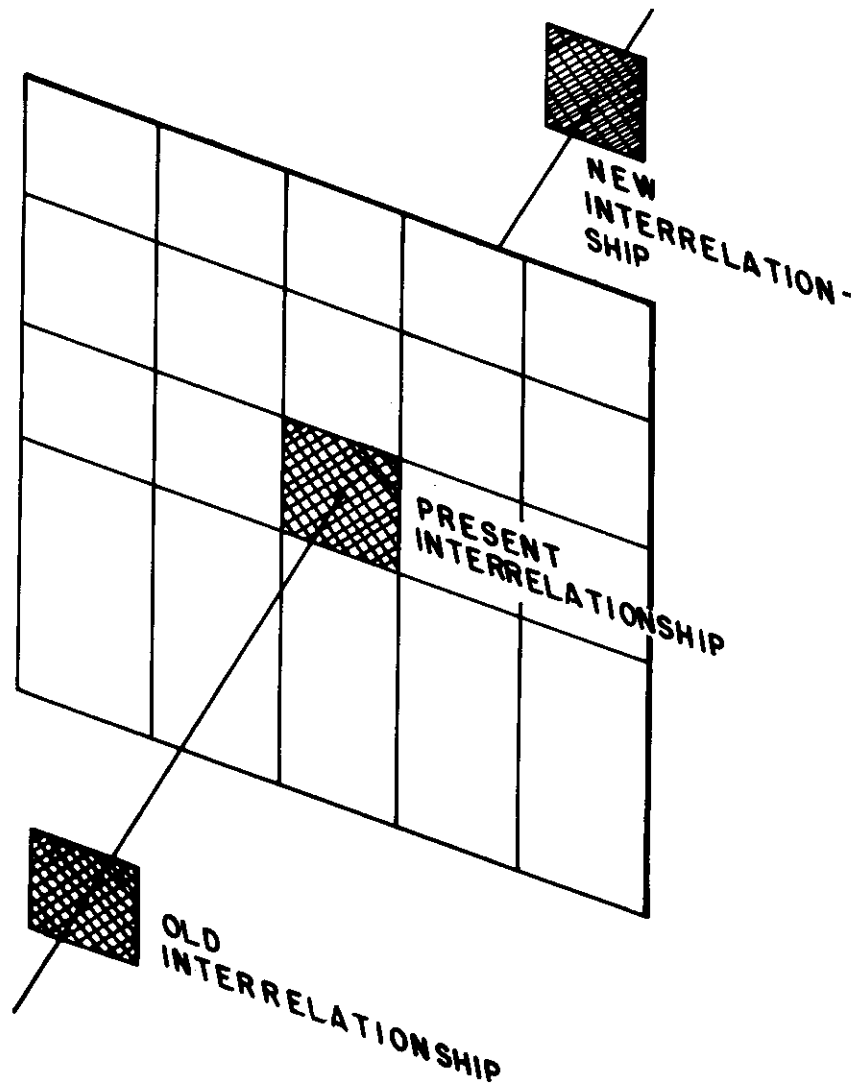
## 2. Updating the Matrix

SAIM is designed to indicate interactions and to provide a means for describing the interactions within a system at a given time. The effects of developmental changes that occur are taken into account by updating the matrix. The matrix remains as a constant framework into which the changes in system elements can be incorporated as they occur. (See Figure 15.)

System development is a dynamic process which includes a great number of activities that are concerned with a large number of elements. Though some of these activities are carried out in parallel, the process is essentially sequential and marked by a series of choices. The time pressure that is characteristic of weapon system development tends to freeze-in all previous choices, making them to some extent irrevocable.

The system matrix reflects this sequential process. At the beginning of the design process, a matrix may be a general set of headings that can be applied to any weapon system. Thus, a missile weapon system starts with a set of general requirements such as range and kill probability; these are put into the matrix. Then, from many alternatives, a type of propulsion, a type of warhead, a method of guidance, and a type of airframe are selected. Where the matrix has had a generalized set of headings labeled "subsystems," each with its modular set of parts and characteristics, it now has a subsystem called "propulsion" and a subsystem called "guidance," etc., each with some defined parts and characteristics. The direct connections can now be indicated, and the analysis, using the model, begins. Where alternatives are being considered, each can be entered into the matrix in turn and played against requirements and components that have already been defined so as to determine their relative effects. Thus, the matrix is constantly being modified, with each design decision and each design development being entered into the matrix and its effects on other elements being determined.

Ultimately associated with the sequential nature of the development process is the decrease in degree of freedom remaining for the designer as the development progresses. Once a guidance system type has been decided upon from the array of possible guidance systems, choice of type and size of airframe or warhead has been narrowed. If type of guidance



RB-2568-13

FIG. 15  
UPDATING THE MATRIX

system and airframe also have been chosen, the choice of warhead has been narrowed even further. This process continues with fewer and fewer alternatives remaining. An example of this that may be familiar to human factor specialists is the development of the first-line maintenance program for a missile. In simplified terms this can be diagrammed as shown in Figure 16.

### 3. Operational Times

The sequence of system operations enters the model as an integrating element. Human components are integrated with mechanism components and with facilities by operations. For example, an operation calls for an operator to flip a switch on a console that is located in a control room. The operator, the console, and the control room are all integrated in time. Each operation that is identified in the matrix has an operational time associated with it.

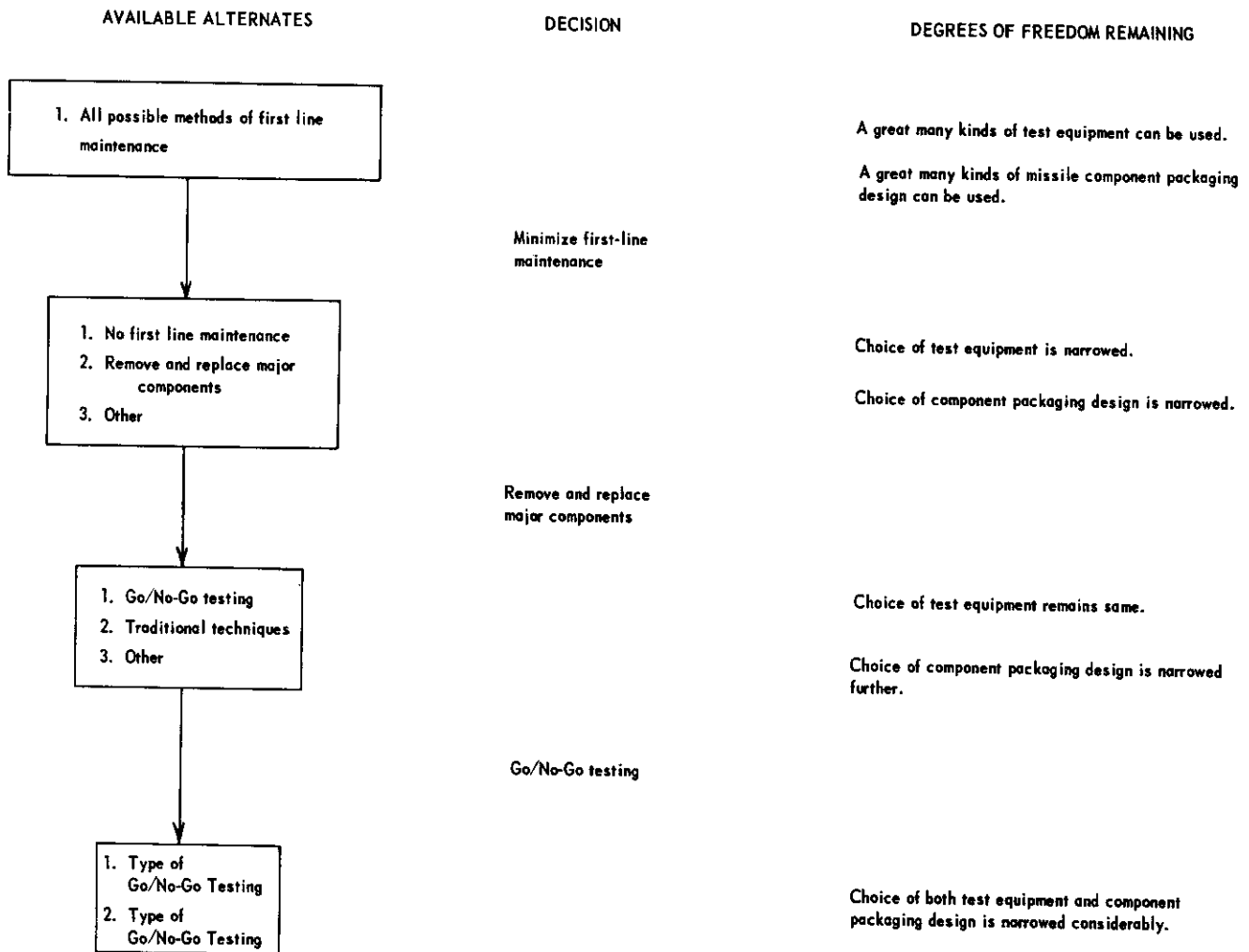


FIG. 16

RB-2568-14

EXAMPLE OF DECREASING DEGREES OF FREEDOM REMAINING AS  
SYSTEM DEVELOPMENT PROGRESSES

*Contrails*

## USING THE MODEL

### A. General

SAIM, a descriptive rather than an evaluative model, provides a way for the systems analyst or the systems manager to maintain an integrated overview of a system and to include and contain changes and developments as they appear.

### B. Analysis and Synthesis

System analysis and system synthesis are two aspects of the problem-solving process that is a basic part of the weapon system development effort. Analysis is the examination of a whole to distinguish its parts and elements separately or in relation to the whole, while synthesis is the combination of parts and elements to form a whole. Both definitions employ the concept of a whole made up of integrated or interrelated parts.

Both analysis and synthesis are employed continuously throughout the weapon system development program, and the construction of the system model makes it of particular value for both purposes. The model is an analyzer because it is a framework with a built-in requirement for explicit consideration of each of the parts of the system and their relationships with each other and to the system as a whole. The model is a synthesizer because it is a device incorporating all system parts into a unitary framework demanding an accounting of the over-all system purposes and requirements as well as consideration of system integrators.

#### 1. Analysis and Synthesis of System Requirements

The mission assigned to and the requirements and constraints placed upon a weapon system at its inception establish the design problem, its assumptions, and its limitations. Accordingly, these requirements and constraints profoundly affect the direction of the developmental effort and establish the basis for evaluating its success. Requirements and constraints come in many forms, both explicit and implicit. These forms include:

- Confidential*
1. Formal statements of system requirements that in some cases are paragraph-long and in others book-long.
  2. Contractual documents that cover dollars, schedules, and specifications for hardware at every level.
  3. Regulations that establish formal service or branch policies.
  4. Less formal policy statements such as those applicable to maintenance and personnel, in the form of reports, letters, etc.

To assure the basis for a coherent and cohesive weapon system program, all such requirements and constraints must be analyzed and synthesized to form a complete, explicit set. Experience with complex weapon systems over the past few years abounds with examples of penalties paid in terms of performance, dollars, and time for efforts to work among unresolved, incompatible, or misinterpreted system requirements and constraints. Recognition of this experience is evidenced by the urgent efforts presently expended by weapon system contractors on the establishment and maintenance of extensive sets of statements in documents variously known as "design objectives," "design requirements," or "design bibles." Most of this effort has been expended on the interpretation and establishment of specific design requirements applicable either to the missile itself or, to some extent, to the test equipment. In most programs, requirements applicable to support activities, to facilities, and especially to human elements do not receive comparable analytic-synthetic effort at this most critical stage of development.

The system model is designed to be used directly in analysis and synthesis of system requirements and constraints. As pointed out in the sections describing the construction of the system model, requirements and constraints are categorized as "determinants." These determinants, which make up the first section of the matrix, are a broadening of the more usually encountered approach to "requirements." In the model, the determinants include and integrate support requirements as well as operational requirements; the inputs from other systems; and constraints such as physical environment, resource limitations, dollars, and schedules. Analysis and synthesis of these determinants, using the system model, involve the following general steps:



## a. Explication of the Original System Requirements and Constraints

This explication involves the analysis of each part of the statement of requirements in order to determine any wider implications that may not readily be apparent. For example, a simple requirement statement may read: "The missile is to be carried on a heavy bomber." "Heavy bomber" implies that the missile will be part of the SAC arsenal. The wider implications here include requirements deriving from the fact that SAC will have the missile. Accordingly, SAC policies on maintenance, personnel, deployment, and operations now must be included as part of the requirements package. As part of this explication process, the headings of the determinants section of the model are used both as a way of organizing the requirements, inputs, and constraints, and as a check list to assure that no pertinent area is overlooked. All known determinants are then entered into the model. As a highly simplified illustration of this process, consider the relatively low level problem of reloading a fighter aircraft for combat. The system in this case (a minor subsystem of a total weapon system) is called the "reloading system." The initial requirement is stated as, "Aircraft will be reloaded with armament, fuel, and oxygen, and ready to go in less than 15 minutes."

This requirement is expressed in the terms that appear as determinants in the model's classification scheme. The statements that are entered in the matrix are:

I. Function (mission)--Reload aircraft with armament, fuel, and oxygen.

II. Performance Requirements

A. Operational

1. All loading operations will be completed in less than 15 minutes, beginning at the time the aircraft wheels stop and ending with the aircraft ready to go. Load will consist of one missile on each wing and full fuel and oxygen load.
2. All operations will be safe for the personnel involved by industrial standards.

3. All devices and operations that are involved will have a reliability of 0.99 plus.

B. Support (drawn from over-all system requirements)

1. No warmup will be required for any loading device.
2. All loading devices will employ remove/replace maintenance and be reparable on base.
3. All loading devices will be portable or mobile.
4. All loading devices will have a two-year operating life.

III. Inputs from Other Systems--All loading devices will require no inputs from other systems other than service items such as fuel or oil.

IV. Constraints

A. Physical Environment--All climate, all weather.

B. Resource Constraints

1. No 5-level or higher skill will be required.
2. Only common materials will be utilized.

C. Cost (abstracted from total system costs)

1. R&D--All loading equipment costs will be less than \$100,000 to R&D.
2. Production and Training--Purchase and training costs per aircraft loading set will be less than \$100,000.
3. Operational--(Undetermined until design is formulated).

D. Schedule Time (abstracted from over-all system schedules)

- Continued*
1. R&D--From start--12 months.
  2. Production and Training--From R&D completion to delivery of first complete loading set f.o.b.--12 months.
  3. Operational--From f.o.b. to first unit being operational--12 months.

b. Tracing the System Determinants through the Matrix

Each determinant is traced through the matrix and is interplayed with other determinants. Identification of possible interactions and recognition of known interactions between matrix entries establish the basis for specific analyses of tasks which must be undertaken and assumptions which must be made. The tracing of determinants through the matrix also is a means for deriving other requirements and constraints that become apparent only from such continued analysis. An oversimplified example of such a derivative requirement is a case where two initial requirements are:

1. The vehicle will be capable of flight at altitudes of 100,000-200,000 feet.
2. The vehicle will be manned.

The interplay of these two requirements suggests, among other things, examination of the physical environment at the required altitude and of the pertinent environmental limitations of man. This examination should result in a requirement for a means of maintaining a suitable environmental envelope for the operator at the designated altitude.

To further illustrate this step, consider again the aircraft reloading example employed in the preceding section. In this example, there is an operating performance requirement for safety of personnel. By tracing this one requirement through a matrix in which the determinants developed in the example are used, it might be noted that this safety requirement directly affects the operational requirement that deals with reloading armament, fuel, and oxygen, and also the support requirement that deals with the portability or mobility of loading devices. This examination results in an expansion of the requirement with statements such as:

1. Fuel and armament will not be loaded simultaneously.
2. Portable loading devices, with load, will weigh less than 65 pounds per human handler.

By continuing a little further with this example and tracing the newly derived requirement concerning nonsimultaneous fuel and armament loading through this same matrix, it is found that the original operational requirement for reloading to be completed in less than 15 minutes is affected. An analysis is indicated, and the reloading requirement might now read, "All loading will be completed in less than 15 minutes beginning with armament loading which will be completed in less than 5 minutes, followed by fuel loading which will be completed in less than 10 minutes. Oxygen will be loaded simultaneously with the other loading operations." This detailing of the time requirements might lead to a derived requirement that, "all loading equipment will be ready at the loading area when the aircraft comes to a stop."

## 2. Analysis and Synthesis of System Functions

Though the research and development process in missile systems is often described as a series of distinct phases that follow one upon the other, it is more properly a series of phases that overlap, parallel each other, or flow unevenly one into the other. This uneven progression is particularly true of that part of the process which translates the requirements and constraints of the system into an organized program for design implementation.

The first step of this process is the selection and definition of the functions to be implemented. A system function is defined as "any function required for the attainment of a given system state," or as "any human or instrumented capability, or combination of these, that may be used to satisfy a system requirement."<sup>1/</sup>

A function does not usually exist as an abstraction except in the initial planning stages. Its existence, in the last analysis, depends upon the establishment of certain operations to be performed by man-mechanism combinations. Consequently, functions and functions analysis

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<sup>1/</sup> Erickson, C. J., and G. F. Rabideau, Function and Task Analysis As a Weapon System Development Tool, NAI-57-1148, Northrop Aircraft, Inc., 2 October 1957.

# Contrails

are probably best thought of in terms of real or implied operations. With this in mind, examples of functions at different system levels may be grossly specified as propelling, guiding, arming, system testing. Some functions at a lower level and not as easily recognized as such are fuel flowing and track monitoring.

The functions selected to be implemented vary from missile system to missile system. Some functions are general enough and repeated consistently enough to be reflected in the names of departments such as propulsion departments, armament departments, and electronics departments, found in almost every missile company. Usually, the majority of functions that are unique to a specific weapon system are those that involve equipment and operations in the nonvehicle aspects of the system. It is in this area that there is greatest latitude in functions selection.

The selection of functions is accomplished in a variety of ways, several of which are used in the course of any single weapon system development. Some functions are selected on the basis of previous design practice within the contractor organization. Some functions are selected by the contractor to reflect current military organization and procedures, while others are imposed (by the military customer) in an effort to make use of the result of work and money that have already been expended on other systems. Many functions are defined uniquely out of the analysis and synthesis of determinants. In practice, most functions are selected in conjunction with the primary requirements analysis effort, though some functions are selected at later stages of the weapon system program.

Functions analysis involves (1) the establishment of the requirements and constraints pertinent to each function in order to establish the bounds within which the design of that specific function can be undertaken, and (2) the establishment of a means of evaluating alternative design possibilities. Functions synthesis involves the examination of the interplay of function upon function and their constraint operations within the bounds of the system's determinants, and serves to determine or derive additional functions that may be required.

The analysis and synthesis of a system's function by use of SAIM would generally include these steps:

## a. Selecting and Identifying Initial System Functions

This involves a systematic review of the determinants in order to make an initial determination of the functions required to meet them. For example, "missile system" identifies the existence of a propulsion function and an airframe function. The system's requirement to destroy a target identifies the existence of an armament function. The system's requirement to be in the field two years identifies a maintenance function and a storage function.

Using the aircraft reloading example, a systematic review of its determinants provides a ready identification of the following functions:

1. Armament loading
2. Fuel loading
3. Oxygen loading
4. Equipment maintenance

## b. Tracing the Initially Identified Functions through the Matrix

Each function is traced through the matrix and interplayed with other identified functions and the system determinants to derive other functions that are needed and to determine whether there is any overlap of functions. An example of this is the determination of an interaction between the maintenance function and the armament function, which results in the selection of specific test functions.

## c. Establishing a Submatrix for Each Major Function

The submatrix for each function is a system model in itself. To analyze the function, a set of function requirements must be drawn up, based on over-all system requirements and on the nature of the function to be performed. An example of this: the determinants for the propulsion subsystem, which include such items as rate of fuel flow, thrust, specific impulse, etc. It is the establishment of these function requirements and constraints that provides the basis for evaluating any proposed implementations of the function. The submatrix also requires that the components of the function and its integrators be identified and analyzed.

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In the aircraft reloading case, a submatrix is established for each of the functions that have been identified. The submatrix for each function includes as its determinants items that are subsumed under, derived from, or identical with the determinants in the matrix of the entire loading system. For example, in the armament loading function submatrix, the determinants are identical with those of the loading system, with the exception of those that are subsumed such as:

1. All loading operations will be completed in less than 5 minutes (falls within 15 minutes allowed for reload operations).
2. R&D costs will be less than \$20,000 (falls within \$100,000 assigned for all reload R&D).
3. Production and training costs will be less than \$6,000 per loader (falls within \$100,000 assigned for all equipment).

The components and integrators in each submatrix are identified. It is initially possible to enter into the submatrix those components that are involved in the function before any new devices are conceived. In the armament loading submatrix, such items are the missile, the missile container, and the aircraft wing. The constraints that are being imposed on a function can quickly identify other components. The cost constraints on the armament loader may quickly define it as a primarily manual operation which identifies a human operational component. Tracing each defined element through the matrix leads to further identifications. If it is assumed that the missile in the armament loading function weighs 100 pounds, it is quickly determined that two men are required when the missile component is interacted with the human component. The height of the aircraft wing above the ground when interacted with the human component calls for the inclusion of a platform. The use of two men creates the need for integrators such as communication and organization. The components that are entered in the armament loading submatrix are the following (see Figure 17):

1. Missile
2. Missile container
3. Aircraft wing
4. Human operational component
5. Human operational component
6. Missile loading device
7. Platform

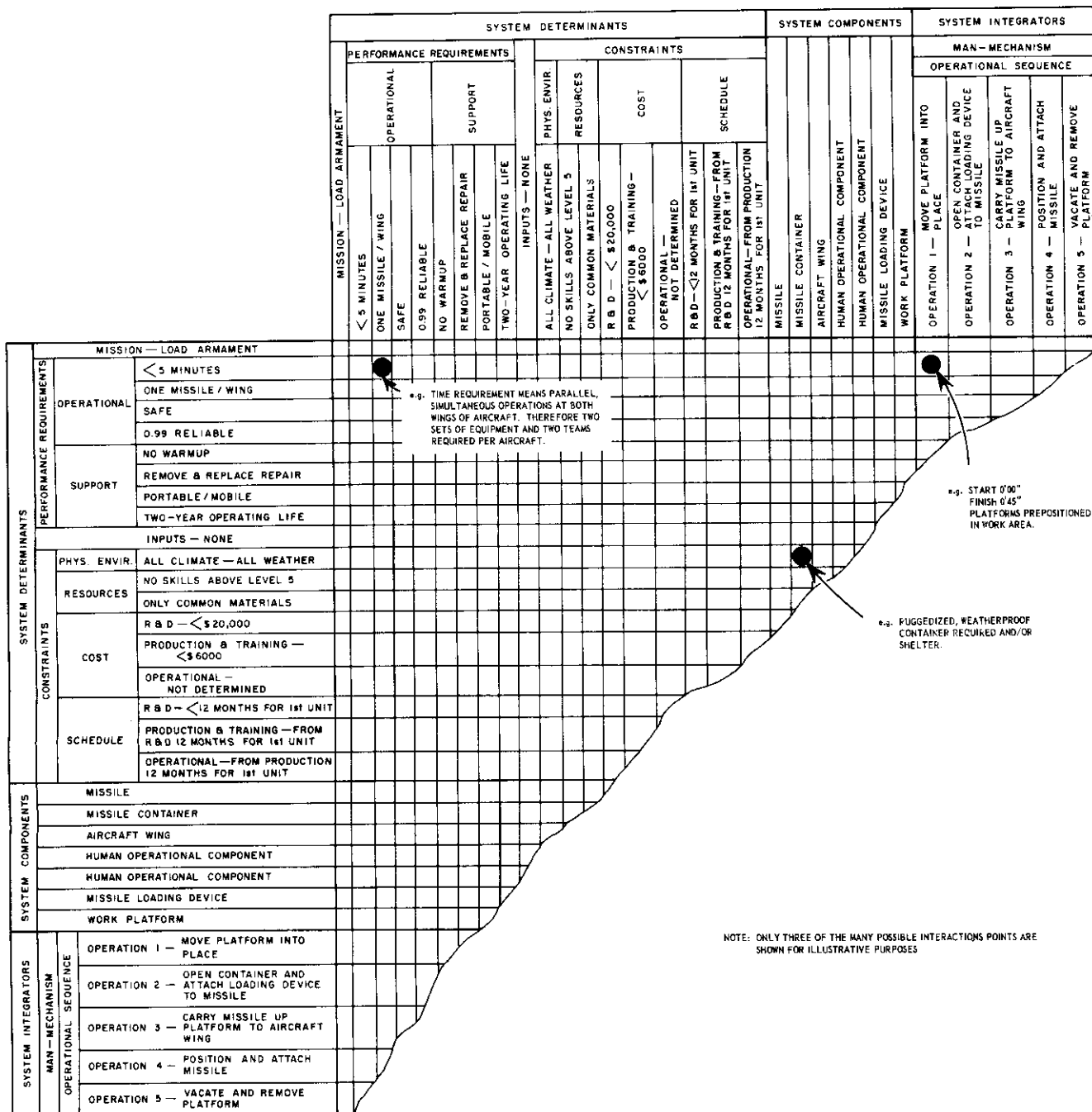


FIG. 17

EXAMPLE OF A SUBMATRIX OF AN ARMAMENT LOADING SUBSYSTEM



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d. Synthesizing Function Requirements and Components in the System Matrix

The results of the submatrix analysis and synthesis are put into the over-all system matrix. The synthesizing of the functions into the system matrix helps eliminate overlap and incompatibility between functions. It also provides an opportunity to review the initial functions selected as well as the requirements of the system for adequacy and completeness.

In the aircraft reloading case, this synthesis points up the combination of such things as operations and work area layouts of each loading function. Determination is made of potential interference and incompatibility, as well as opportunities to distribute or combine work loads. Here is seen the possibility for switching the armament loaders to oxygen loading after the first 5 minutes.

e. Replacing Functions by Descriptions of Their Implementations

As functions are implemented, their places in the system's matrix are filled with descriptions of the actual designs that have been made. These, in turn, are replaced by descriptions of the measured attributes of the mechanisms, men, and facilities that are built, trained, or selected to implement the designs. Each step of replacement is accompanied by an evaluation of the resulting implementation against the determinants and by a comparison of resulting implementation with the previous matrix entry.

C. Using the Model as an Evaluation Tool

System evaluation continues throughout the weapon system program to ascertain how well the program effort is meeting the determinants that have been established for the system. Criteria for evaluation are derived from the system determinants. The underlying evaluation questions applied either to existing or to proposed entities are: How well does the program meet the performance requirements of the system and of its components within the imposed constraints and with the given inputs? Which alternative best meets the performance requirements of the system and of the components within the imposed constraints and with the given inputs?

The system model is constructed to aid in answering these questions. By incorporating within one framework the system determinants, the system components (as functions, designs, or existing entities), and their interactions, it brings compactly together all pertinent information. By systematizing the examination of interactions, it helps avoid the common error of leaving out significant factors. By using both quantitative and qualitative data, it avoids many simplifying assumptions which tend to obscure effects significant to evaluation.

It should be clearly understood that the system model cannot design anything by itself. The design or proposed implementation of a system function is a creative act depending on the skill and imagination of the designers. Once an implementation or design is conceived, however, it can be included in the system model and evaluated in terms of its direct connections with or effects on other system components and the system determinants. Analysis of these interactions results in a determination of how well this implementation might fulfill the system function and meet its requirements, within its constraints. Alternative designs can be entered into the model one at a time for purposes of comparison. The evaluation thus achieved is in terms of performance, dollars, and schedules. By continuous updating of the model with information available from the design and test efforts, a continuous integrated evaluation effort may be maintained.

## 1. Evaluation of Proposed Designs

Evaluation of a proposed design using the system model follows the general steps listed below:

### a. Putting Information concerning the Proposed Design into the Matrix

The proposed design is evaluated primarily in terms of the adequacy with which the design conforms to the determinants such as performance, costs, and schedules. The proposed design itself is cast into matrix form, and each of the proposed components is described in terms of its dynamic characteristics (inputs, outputs), physical characteristics, and environmental characteristics.

## *Conrails*

b. Tracing the Proposed Design through the Matrix

This step provides an indication of probable adequacy within the given constraints. Systematically following the design through the matrix format provides a means of assuring that all components, including human components and facilities, are included in this consideration in a systematic way and are not overlooked or assumed away. Analytical or judgment estimates are made of the nature of each of the many element interactions.

c. Entering Results from Analysis and Synthesis in the Over-all System Matrix

Seldom does a design exactly meet the determinants of the system. In some areas, it does better than expected; in others, not quite as well. By entering these results into the over-all system matrix and tracing their effects, it is possible to ascertain whether these differences significantly affect the other components of the system or the system as a whole; or whether the deviations from desired performance, costs, or schedules remain tolerable.

Where alternative designs are proposed, each design can be processed through the system model in turn, and the results can be compared on a determinant-by-determinant basis.

Using the aircraft reloading case again--two missile loading devices are proposed for the armament loading function. Each is described in terms of the classification system used in the model: inputs, outputs, physical characteristics, and environment characteristics. The descriptions of the loading devices are entered into the armament loading submatrix, one at a time. The effects of the characteristics of each device are estimated or calculated, and finally the two proposals are compared in terms of performance (such as loading time, safety, and reliability), in terms of support requirements, and in terms of constraints (such as costs and schedules). A further comparison can be made, where required, by seeing the effects of each proposed loader on the synthesized aircraft loading system matrix.

## 2. Evaluating Existing Developments

The process suggested for evaluation of a proposed design applies here, using descriptions of actual components or operations in place of design.

### 3. Evaluating Changes

The process suggested for evaluation of a proposed design applies here also. The need for evaluating changes makes continuous demands on the personnel responsible for a weapon system program, for each proposed change is analyzed as to its effect on the over-all system, its performance, its costs, and its schedules. The system model routinizes this process and puts it into a form that can be repeated from change to change. Every proposed design change finds its origin and justification in a changed determinant or the attempt to satisfy a given determinant. The model readily lends itself to a form of analysis which varies a determinant, follows the results of such variation through many connections, and eventually shows the related increment in performance, costs, and time, and shows the demands on both material and human resources.

#### D. Using the Model as a Development Planning Tool

By organizing the description of the system and its interactions, the model provides a means for systematically outlining the elements and characteristics that should be considered by those charged with system planning. By requiring the ordered consideration of system interactions in the matrix, the model provides a means for establishing which items are pertinent to the system and its development, and whether they are knowns or unknowns. An examination of the interaction spaces of the matrix at any time should provide an aid to planning the activities needed to diminish the unknowns.

Each blank interaction space indicates that there is no direct connection between the two elements forming the cell. Each interaction space marked as having a direct connection indicates that there is a direct connection between the two elements forming the cell. Initially, there may be a number of interaction spaces containing question marks. These question marks indicate that it is not yet known whether or not direct connections exist. Further investigation is required to determine the nature of these relationships. A survey of those three kinds of interaction conditions provides the planner with the following:

1. A tabulation of interactions that are in question and therefore require that action be taken to determine their status.
2. A tabulation of direct connections that can be examined to determine to what degree these have been identified and analyzed. It is possible then to arrange these interactions in the order

of their importance to the system and to set up a pattern of action for completing the interaction statements.

## 1. Determining the Information Requirements

By examining the system through the use of the model, it is feasible at any time to determine systematically the information required for the weapon system programs and to organize a plan for obtaining this information.

## 2. Determining the Status of Available Information

The model is used as a device to review the areas in which needed information is on hand or is lacking. This review is accomplished by a tabulation of the status of the interaction spaces in the matrix similar to that suggested for planning above.

- a. The interaction spaces where it is not known yet whether there is or is not a direct connection have a high priority as "information need" areas.
- b. The interaction spaces that are identified as having direct connections are reviewed to determine the adequacy of the information on hand and to examine the effort that is planned or in progress to obtain needed information.

## 3. Establishing Information Need Priorities

The tabulation of the status of available information is analyzed for purposes of ranking in order of priority. The priorities vary somewhat from system to system, but an underlying order of priority is reflected in the way the system elements are ordered in the model. System determinants must have first priority because of their relatively larger effect on all parts of the system. The components follow the determinants in priority, but have an internal order of priorities that is a function of the particular kind of system being developed. The integrators are of importance but in most cases are dependent on prior definition of determinants and components.

## E. Planning for Development

With definite information requirements ordered on the basis of priority, those charged with the task can proceed with developmental planning in an orderly fashion. Such planning includes efforts in analysis directed to resolving unknowns, and efforts in testing directed to verifying design and to checking assumptions as well as to checking interpolations and extrapolations that have been used in areas of doubtful information. It also involves the determination of the need for special technical skills in the developmental program.

## F. Planning for Research

Similarly, the model can be used to tabulate and to arrange in terms of priority the areas of ignorance, the areas of on-going research, and the areas of planned research as they apply to weapon system research efforts (as distinguished from weapon system development efforts). A matrix describing research effort can then be constructed and "overlaid" on a typical weapon system matrix to determine what areas have been overlooked or already covered.

## G. Using the Model as a Management Control Tool

Management control of a weapon system program is highly dependent on and extremely sensitive to the degree of "visibility" of the program to those responsible for its management. The current efforts and developments that take place throughout the many facets of a program must be visible to the program management so that those responsible can distribute intelligently the available resources, as well as take indicated corrective action. Also, the possible effects of alternative decisions must be visible to some degree, or decision-making becomes relatively less efficient.

SAIM can be used directly as an aid to providing both kinds of visibility. By describing the system as it is at any time, and by lending itself to being continually updated, SAIM provides a means of keeping track of the on-going program effort. If desired, the matrix of the current system can be overlaid with a matrix describing the areas of responsibility for system effort which will indicate to management that all the system is covered, and with minimum overlap. By entering the results of alternative decisions in the matrix and tracing their predicted results through their many interactions, the matrix provides in a sense the kind of visibility required as the basis for intelligent decision-making.

Appendix A

**SUGGESTED CLASSIFICATION OF HUMAN OPERATIONS COMPONENT  
AND MECHANISM TERMS FOR USE IN SAIM**

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SUGGESTED CLASSIFICATION OF HUMAN OPERATIONS COMPONENT  
AND MECHANISM TERMS FOR USE IN SAIM

I. Mechanism Output

A. Display

1. Visual

a. Type

- (1) Label
- (2) Indicator (Moving Pointer, Moving Scale, Counter, Light, Scope)

b. Characteristics

- (1) Color
- (2) Brightness
- (3) Contrast
- (4) Temporal Characteristics (Frequency, Duration, Rate of Occurrence, Rate of Change)
- (5) Configuration (Shape, Size, Texture)
- (6) Movement (Direction, Regular, Irregular, Rate, Acceleration)
- (7) Other

2. Audio

a. Type

- (1) Pure Tones

(2) Complex (Nonspeech) Sounds

(3) Speech

b. Characteristics

(1) Audio Frequency (CPS)

(2) Intensity

(3) Signal/Noise Ratio

(4) Temporal Characteristic (Frequency of Occurrence,  
Duration, Rate)

(5) Configuration (Direction, Sound Pattern)

(6) Movement (Direction, Regular, Irregular, Rate)

(7) Other

3. Tactile

a. Type

(1) Light Touch

(2) Gross Touch

(3) Vibratory

b. Characteristics

(1) Texture

(2) Configuration (Shape, Size, Sequence)

(3) Temporal (Frequency of Occurrence, Duration, Rate)

(4) Intensity

*Contrails*  
(5) Temperature

(6) Movement (Direction, Regular, Irregular, Rate, Acceleration)

(7) Other

4. Proprioception

a. Type

(1) Static

(2) Dynamic (Movement)

b. Characteristics

(1) Pressure Sensitivity

(2) Tension Sensitivity

(3) Direction Sensitivity

(4) Rate Sensitivity

(5) Rate of Change Sensitivity

(6) Other

5. Other (Vestibular, Somaesthetic, Smell, Pain, Temperature)

B. Nondisplay

1. Energy (Power, Vibration, Sound, Heat, Radiation)

2. Material (Gases, Liquids, Solids)

## II. Human Input

### A. Display<sup>1/</sup>

#### 1. Visual

##### a. Type

(1) Label

(2) Indicator (Moving Pointer, Moving Scale, Counter, Light, Scope)

##### b. Characteristics

(1) Color

(2) Brightness

(3) Contrast

(4) Temporal Characteristics (Frequency, Duration, Rate of Occurrence, Rate of Change)

(5) Configuration (Shape, Size, Texture)

(6) Movement (Direction, Regular, Irregular, Rate, Acceleration)

(7) Other

#### 2. Audio

##### a. Type

(1) Pure Tones

(2) Complex (Nonspeech) Sounds

(3) Speech

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<sup>1/</sup> Redundancy of some terms in Mechanism Output and Human Input sections is provided in order to permit separate consideration of a system element where desired or required.

b. Characteristics

- (1) Audio Frequency (CPS)
- (2) Intensity
- (3) Signal/Noise Ratio
- (4) Temporal Characteristic (Frequency of Occurrence, Duration, Rate)
- (5) Configuration (Direction, Sound Pattern)
- (6) Movement (Direction, Regular, Irregular, Rate)
- (7) Other

3. Tactile

a. Type

- (1) Light Touch
- (2) Gross Touch
- (3) Vibratory

b. Characteristics

- (1) Texture
- (2) Configuration (Shape, Size, Sequence)
- (3) Temporal (Frequency of Occurrence, Duration, Rate)
- (4) Intensity
- (5) Temperature
- (6) Movement (Direction, Regular, Irregular, Rate, Acceleration)
- (7) Other

4. Proprioception

a. Type

- (1) Static
- (2) Dynamic (Movement)

b. Characteristics

- (1) Pressure Sensitivity
- (2) Tension Sensitivity
- (3) Direction Sensitivity
- (4) Rate Sensitivity
- (5) Rate of Change Sensitivity
- (6) Other

5. Other (Vestibular, Somaesthetic, Smell, Pain, Temperature)

B. Communication

1. Types

- a. Oral
- b. Written
- c. Other (Drawings, Pictures, Gestures)

2. Characteristics

- a. Corrections
- b. Temporal (Rate, Duration)
- c. Information

C. Stored

1. Learned (Training, Experience)
2. Innate Ability (Psychological, Physiological)

D. Other

III. Human Output

A. Control

1. Types
  - a. Discrete Adjustment
  - b. Continuous Adjustment
2. Characteristics
  - a. Force
  - b. Direction
  - c. Displacement
  - d. Temporal Characteristics (Frequency, Duration, Rate, Acceleration)
  - e. Other
3. Body Member (Anthropometric Considerations)

B. Communication

1. Types
  - a. Oral
  - b. Written
  - c. Other (Drawings, Pictures, Gestures)

2. Characteristics

- a. Correctness
- b. Temporal (Rate, Duration)
- c. Information
- d. Other

C. Noncontrol Activity (Assembling, Material Handling, Positioning)

D. Physiological

IV. Layout

A. Work Area

- 1. Configuration (Dimensions, Shape)
- 2. Flow Paths
- 3. Linkages
- 4. Working Position (Standing, Sitting)
- 5. Compatibility<sup>1/</sup>
- 6. Other

B. Work Place

- 1. Panel (Fixed Instrument and Control)
  - a. Types
    - (1) Individual Operator
    - (2) Group

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<sup>1/</sup> Compatibility, for example, may include not only display-control relationships but also display-display and control-control relationships for different positions in a work area.



b. Characteristics

- (1) Configuration (of over-all panel) (Size, Shape)
- (2) Arrangement of Displays and Controls (Number, Kind, Spatial Relationship, Space Required, Compatibility)
- (3) Communication Equipment Arrangement (Number, Kind, Spatial Relationships, Space Required)
- (4) Man-Panel Orientation
- (5) Other (Ash Tray, Writing Space)

2. Work Bench (Nonfixed Instrument and Tools)

a. Types

- (1) Individual Operator
- (2) Group

b. Characteristics

- (1) Configuration
- (2) Equipment Arrangement
  - (a) Fixed
  - (b) Other
  - (c) Man-Work Bench Orientation

V. Mechanism Input

A. Controls

1. Types

- a. Discrete Adjustment (Push Button, Switches)
- b. Continuous Adjustment (Knob, Crank, Handwheel, Lever, Pedal)

## 2. Characteristics

- a. Configuration (Size, Shape)
- b. Resistance
- c. Direction
- d. Displacement
- e. Temporal Characteristics (Frequency, Duration, Rate, Acceleration)
- f. Other

## B. Noncontrol

1. Energy (Power, Vibration, Sound, Heat, Radiation)
2. Material (Gases, Liquids, Solids)