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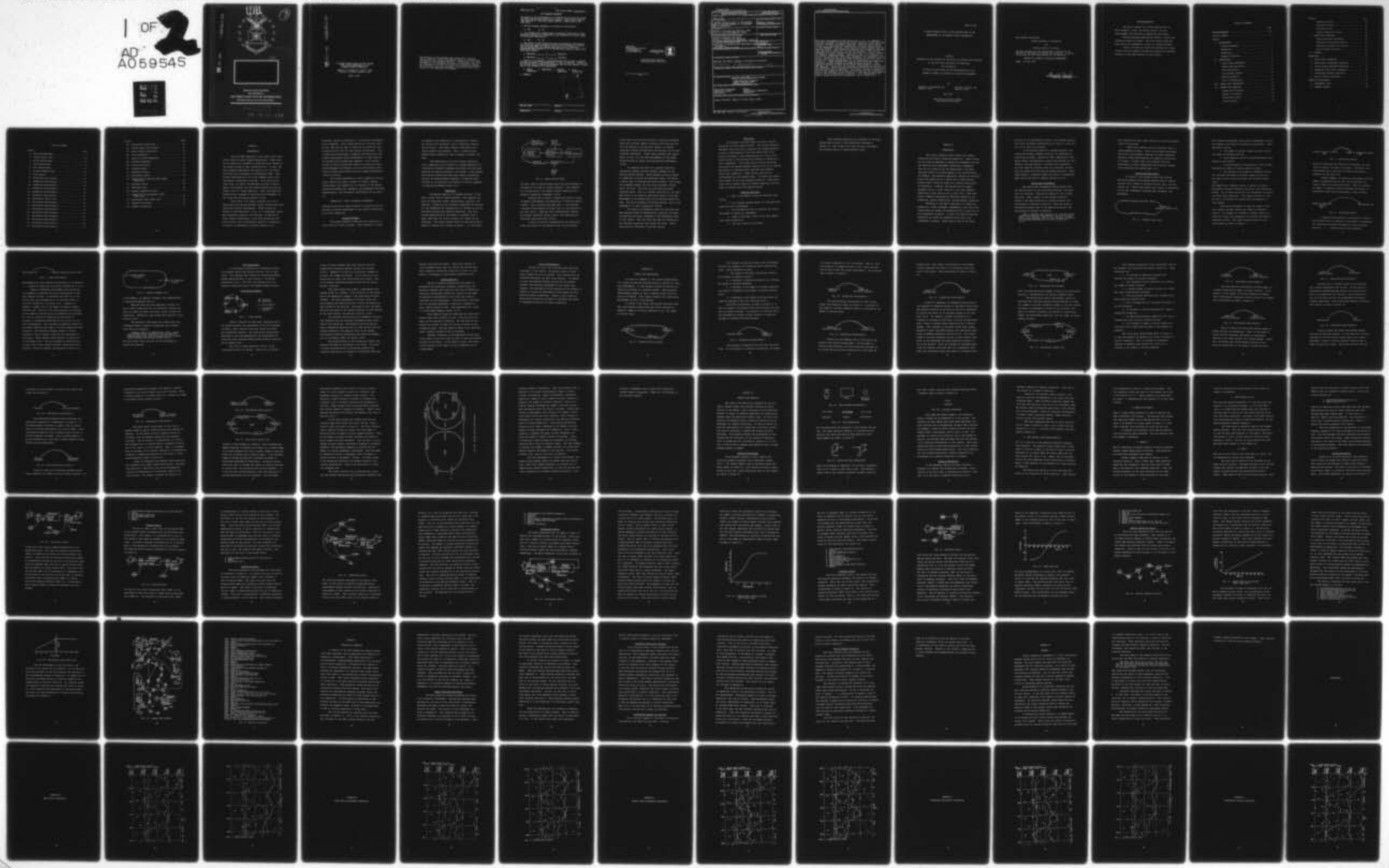

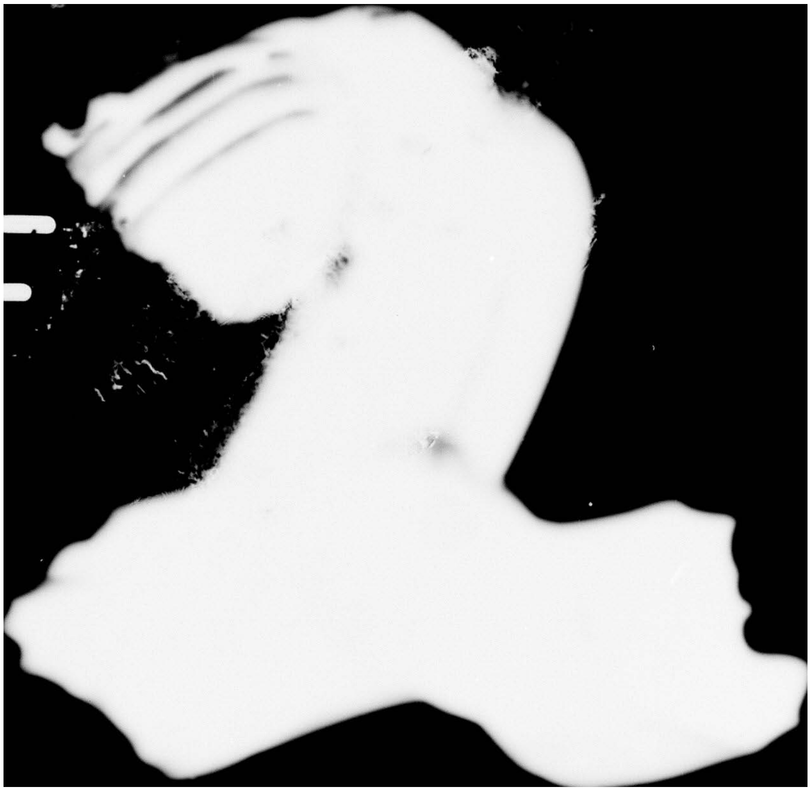

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A SYSTEM DYNAMICS STUDY OF THE FACTORS USED IN THE MEASUREMENT OF AN AIRCRAFT WING'S CAPABILITY

Baldwin G. Fitzgerald, Captain, USAF
Phillip E. Miller, Captain, USAF

LSSR 23-78A

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Reporting requirements of JCS Publication 6, Vol. II, presently are used to assess an operational unit's capability based upon four factors: personnel, equipment readiness, supplies, and training. Provision is also made for consideration of other factors which, in the commander's opinion, might have overriding effects upon the reported status. This method of assessing unit capability focuses upon individual factors in a static relationship. The factors determining a unit's capability are not static but rather interact to create a dynamic process. Capability, then, is a function of the dynamic interaction among men, equipment, and management functions. Looking at any one of these variables in isolation will not provide an accurate measurement of its contribution to a unit's capability. Other systems with similar interaction have been successfully studied through the system dynamics approach. This approach consists of three basic steps: understanding, analysis, and modeling. Unless one can thoroughly understand and analyze all the components and interactions of a system, one can not accurately portray that system's operation. This thesis presents a description of the operation of an aircraft wing through the understanding gained from a system dynamics analysis. Such understanding may lead to greater accuracy in assessing a unit's capability.

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A SYSTEM DYNAMICS STUDY OF THE FACTORS USED IN THE MEASUREMENT OF AN AIRCRAFT WING'S CAPABILITY

A Thesis

Presented to the Faculty of the School of Systems and Logistics
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Logistics Management

By

Baldwin G. Fitzgerald, BA
Captain, USAF

Phillip E. Miller, BA
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June 1978

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This thesis, written by

Captain Baldwin G. Fitzgerald

and

Captain Phillip E. Miller

has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN LOGISTICS MANAGEMENT

DATE: 14 June 1978

Thomas W. Clark Jr.
COMMITTEE CHAIRMAN

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CHAPTER I

INTRODUCTION

Each day USAF operational units report their capability status to major command headquarters. These capability reports are intended to inform the major command of the status of each of their assigned units. In turn, the major command consolidates the inputs of all its forces and relays this information to Headquarters USAF. After further consolidation of all major command inputs, the information is provided to the JCS. Since each service (Army, Navy, Air Force, and Marines) provides a similar report, JCS planners can then develop defense policy consistent with U.S. force capability. Hence the capability reports serve a purpose in both day-to-day management of the forces and long-range planning (3:1-9).

Since there is no single indicator of a unit's capability which can be reported, several factors have been identified as major determinants. These factors are defined in JCS Publication 6, Vol. II, as personnel, equipment readiness, supplies, and training. In addition to these primary determinants, it has been recognized that other factors such as maintenance capability, scheduling decisions, and backorders influence capability and, therefore, should be considered in a qualitative assessment by the commander. While these factors may influence capability, they are not used in computing the capability percentages derived from the four primary determinants. Thus a quantitative percentage is computed and reported for the primary determinants while consideration of other factors is included only as additional comments. Such a method focuses on static factors and tends to overlook the interactions between the elements as well as the dynamic interaction of these other factors with the primary determinants (3:6A-45 to 6A-52).

The factors determining a unit's capability are not static objects but rather interact to create a dynamic process where true capability is a function of the dynamic interaction between men, equipment, and management decisions. Mathematically, this functional relationship can be stated as:

$$\text{Capability} = f(\text{men, equipment, management})$$

Looking at any one of these variables in isolation will not provide an accurate measurement of its overall contribution to a unit's capability.

Problem Statement

The present method of measuring unit capability is best suited to a static process. Each component is looked at separately and measured as a deterministic variable. The factors that determine a unit's capability, however, are not static. They share complex interactions that create dynamic relationships. Thus, a problem exists because static methods are used to measure a dynamic process.

The combination of all such factors impacting a unit's capability can be viewed as a system consisting of interacting information feedback structures that have both positive and negative effects on the system. Other systems with similar interactions have been studied successfully through the system dynamics approach, a technique which "focuses on the structure and behavior of systems composed of interacting feedback loops [1:5]."

Background

The systems approach, or systems thinking, is the basic concept used in system dynamics. This approach consists of three basic steps: understanding, analysis, and modeling. Unless one can thoroughly understand and analyze all the components and interactions of a system, he can not accurately portray that system's operation. Once this initial appreciation of the system is achieved, then a model based upon the classic concept of a system can be developed. The classic systems model has been developed by Edward B. Roberts and is shown as Figure 1. In this model,

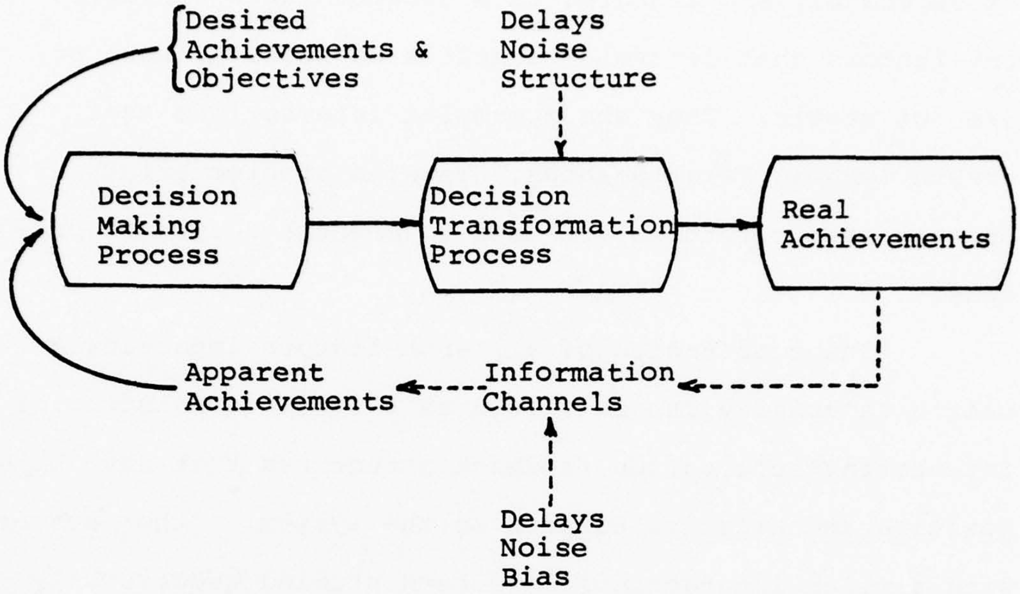


Fig. 1. Basic Systems Model

the basic idea on input-process-output has been expanded to incorporate the ideas of dynamic feedback. Such feedback is a central part of any dynamic system, especially the system of capability assessment (4:676).

Looking now at Figure 1, Roberts has shown an input of Desired Achievements and Objectives to a Decision Making Process. Once a decision has been made, it goes through a Decision Transformation Process; that is, the decision is put into action. Impacting this transformation, however, are several variables: Delays, Noise, and Organizational Structural Characteristics (4:678).

A Delay in decision implementation can drastically affect the result of any decision since the environment within which the decision was made is constantly changing. Noise and Structure impede a decision since they may distort the meaning of the decision (Noise), or present structural hurdles through which the decision can not pass unchanged (Structure). These three variables are responsible, in part, for the Real Achievements of the implemented decision to differ from the Desired Achievements (4:682).

To complete the cycle of a system's operation, Information Channels provide constant feedback to the Decision Making Process. These channels provide a method of comparison of actual and perceived output, and become a second input to the Decision Making Process. Acting upon this feedback channel are also three variables: Delays, Noise, and Bias. The first two have been previously described above. Bias is a further distortion of the feedback since it can cause an inaccurate picture of the Real Achievement to be relayed back to the Decision Making Process. This cycle becomes a continuous process, just as the assessment of a unit's capability (4:591).

The ideas of the Roberts' model and the three systems approach steps of understanding, analysis, and modeling establish the basic framework of the methodology used in this thesis. They also form the basis for determining the important objectives that guided the study. These objectives are discussed in the next section.

Objectives

The direction outlined leads to several specific objectives for this research effort. The initial objective implements the first step in applying the systems approach: to gain an understanding of how the system under study actually functions. This understanding will lead to the identification of the factors that interact to determine a unit's capability. Once these factors clearly have been identified, the second research objective will be to analyze the factors to determine which ones have the greatest effect upon capability. These factors then will be incorporated into the systems model. To design and operate such a model is the final research objective. These objectives lead to several specific research questions that are drawn to further guide the research effort.

Research Questions

1. What is the present system of assessing capability?
2. Can a dynamic systems model of a representative operating unit be developed?
3. Can the model be used to evaluate the current philosophy of capability assessment?
4. Based on the model, what are the key elements that affect capability?
5. Can such a model be validated?

These research questions are addressed in the study through applications of the methodology discussed in Chapter II. This chapter will show the basic philosophy and concepts used in a system dynamics study.

CHAPTER II

METHODOLOGY

The initial research effort within this thesis identified the factors affecting capability. These factors are not directly measured in capability assessment, but are the basis for wing commanders' qualitative judgements. They are not unique to any one organization, but their influence exists in varying degrees in all organizations. For example, from personal experience, weather can adversely affect the capability of a flying unit in Maine during February while having no effect on a similar organization in California. Likewise, the availability of support equipment can be a vital factor to a unit that suddenly experiences a high failure rate in this area. Other such factors commonly recognized as affecting capability are scheduling, supply interactions, and maintenance capability.

Returning to the basic formulation of capability, Capability = f(men, equipment, management), each factor mentioned above can readily be associated with at least one of the independent variables. In fact, the factors affecting capability are those key elements within each of the independent variables. These factors must be the focus of study in the understanding phase of the systems approach. Only after thoroughly understanding the nature of each factor can one move into analysis.

In the analysis phase of a systems approach, the interaction between elements (factors) is represented by causal-loop diagrams. Because of their importance to this thesis effort, representative causal-loop diagrams are discussed in the next section. Following this discussion, two more important analysis steps are discussed: diagramming the system flow and deriving system equations. These steps produce a conceptual model from which a mathematical model can be derived for computer operation (2:13).

Causal-Loop Diagramming

The causal-loop diagramming process begins with the identification of the relationship between individual pairs of variables. These pairs combine to form a feedback loop. When a change in one variable produces a change in the same direction in a second variable, the relationship is defined as positive. When the change in the second variable runs in the opposite direction, the relationship is defined as negative.

> When a feedback loop response to a variable change opposes the original perturbation, the loop is negative or goal-seeking. When a loop response reinforces the original perturbation, the loop is positive [2:9].

The variables are then linked together to form the feedback loops of the system.

Causal-loop diagrams play two important roles in system dynamics studies. First, during model development, they serve as preliminary sketches of causal hypotheses. Secondly, causal-loop diagrams can simplify illustration of a model. In both roles, the diagrams allow the researcher to quickly communicate the structural assumptions underlying the system model (2:5).

Causal-Loop Description

In Figure 2, the primary causal-loop diagram describes feedback relationships between mission capable aircraft (MC), number of scheduled sorties (SS), and maintenance (M). These three factors were chosen as representative of the independent variables men, equipment, and management.

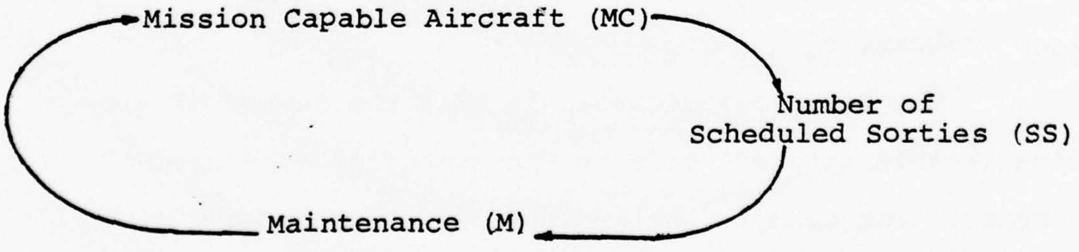


Fig. 2. Primary Causal Loop

This diagram incorporates simple causal hypotheses relating the feedback loop underlying capability measurement. These hypotheses include:

1. The number of mission capable aircraft affects the number of scheduled sorties.

2. More scheduled sorties increase maintenance performed on the aircraft.

3. A greater amount of maintenance on the aircraft decreases the number of mission capable aircraft.

4. An increase in the number of scheduled sorties will decrease the number of mission capable aircraft in the long run due to periodic phase and corrosion inspections.

For simplicity of example, Figure 2 ignores the type of maintenance involved, schedule deviations, and information delays. All of these factors will be considered in developing final loop interaction. This simple figure will only be used to illustrate the step-by-step development of a loop diagram.

The first relationship is that the number of mission capable aircraft effects the number of scheduled sorties. For example, an increase in mission ready aircraft will cause unit schedulers to increase the number of scheduled sorties. The causal representation for this relationship is shown in Figure 3.

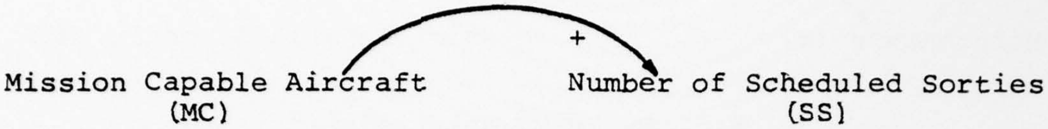


Fig. 3. MC-SS Relationship

The arrow indicates the direction of influence; the sign (plus or minus), the type of influence. Therefore, the relationship has a plus sign signifying the positive character of the link (2:7).

Another example of a positive relationship involves number of scheduled sorties (SS) and maintenance (M). Figure 4 shows the SS-M relationship. Thus, an increase in number of scheduled sorties increases the amount of maintenance which must be performed on these aircraft.

Fig. 4. SS-M Relationship

A negative relationship is illustrated in Figure 5 which depicts that an increase in the amount of maintenance will eventually decrease the number of mission capable aircraft. ". . . unrealistically high readiness

Fig. 5. M-MC Relationship

requirements may cause essential maintenance to be deferred . . . serves to reduce the unit mission capability [7:1-1]."

Figure 6 represents the feedback loop portraying the response of scheduled sorties and maintenance to mission capable aircraft. To determine the polarity of the entire loop, the consequences of an arbitrary change in one loop variable will be traced (2:9). Assume, for example, a sudden rise in the number of mission capable aircraft (MC). The rise in MC makes possible an increase in the number of sorties which are scheduled; MC increases SS. But an increase in scheduled sorties causes an increase in maintenance performed on the aircraft to correct discrepancies. This increased maintenance demand will now tend to decrease the number of mission capable aircraft available. The externally caused increase in MC has triggered a set of internal reactions and adjustments in the system. These changes create pressure in opposition to the change in MC. The loop attempts to maintain MC at a fixed value or goal despite external influences to the contrary. Thus the feedback loop depicted in Figure 6 is

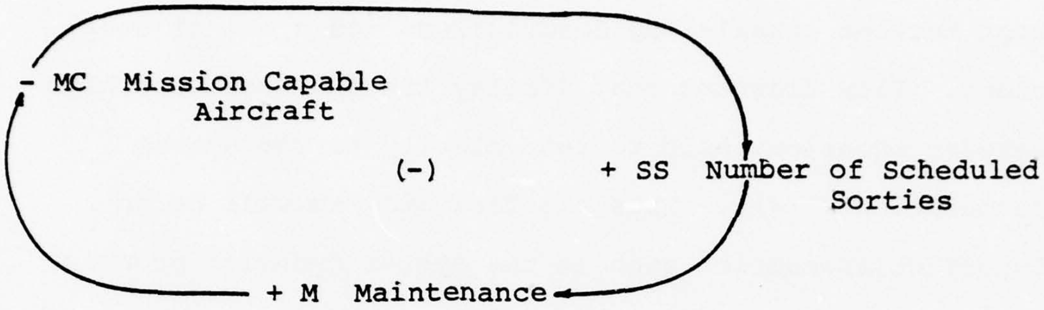


Fig. 6. Primary Feedback Loop

a goal-seeking, or negative, feedback loop represented by a centralized negative sign (-).

When more than one loop comprises a system, the sign of each closed path must be determined, holding constant all other variables (and hence loops) outside the closed path. Eventually, each closed path receives a loop polarity (2:10).

The process of identifying all causal-loop relationships creates a series of hypotheses about observations which are testable.

> Although useful as communication tools, causal-loop diagrams cannot substitute for detailed flow diagrams which must first be constructed before simulation analysis can proceed further [2:12].

The next logical step then will be the development of system flow diagrams.

Flow Diagramming

A flow diagram represents an intermediate transition between causal-loop descriptions and a set of equations. Flow diagrams that display the interrelationships between equations help to lend clarity to the system formulation (1:81). Thus the flow diagram will be an important transition step in the system dynamics process.

Flow Diagram Example

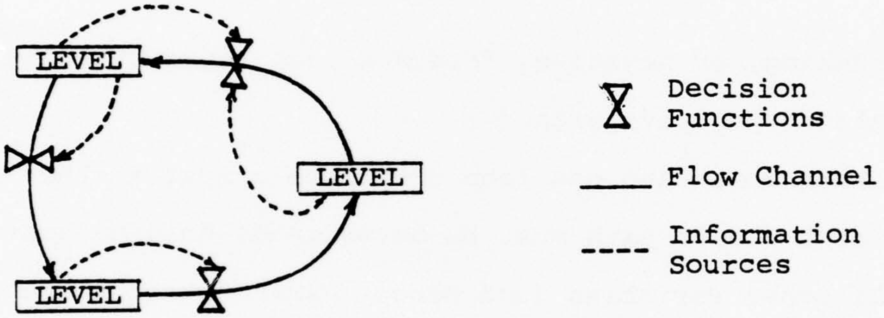


Fig. 7. Flow Diagram

Figure 7 contains the four basic features found in any system and which are represented in the flow diagrams as levels, flows, decision functions (drawn as valves), and information channels. The interaction relationships developed in the loop diagrams will be transformed into these four basic features before system dynamics equations can be formed (1:68).

The first of these features, a level, is the accumulation within the system. "Levels are the present values of those variables that have resulted from the accumulated differences between inflows and outflows [1:68]." Examples of levels are inventories, numbers of aircraft, and number of sorties. If all activity in the system were to cease, the levels would still exist. This is the primary difference between levels and the second feature, flow rate.

Flow rates define the present, instantaneous flow between levels in a system. If all activity in the system were to be momentarily stopped, flow rates would be unobservable. The rates correspond to activity, while the levels measure the resulting state to which the system has been brought by the activity. The rates of flow are determined by the levels of the system according to rules defined by the third feature, the decision function (1:68).

The decision functions are the statements of policy that determine how the available information about levels leads to the decisions. The decision functions pertain both to managerial decisions and to those actions that are inherent results of the physical state of the system. The decision functions determining the rates are dependent only on information about the levels (1:69).

The fourth feature is the information channel that connects the decision functions to the levels. The level of recent business activity influencing ordering and inventory decisions is an example of information affecting decision functions and levels. These four features of flow diagramming have taken the interacting factors from their simplistic causal-loop stage up to a point in time where it is possible to write system equations (1:69).

System Equations

The set of system equations will be capable of describing the situations, concepts, interactions, and decision processes that constitute the idea of capability. Basically, the equation system will consist of two types of equations corresponding to the levels and rates as described in flow diagramming. The equations of the model will be evaluated repeatedly to generate a sequence of steps equally spaced in time. This sequencing will result in a time-linked computer output (1:73).

This computer output will show how the interactive factors react over a period of time. From this data the model can be internally validated. The data must be consistent and logical to show the internal accuracy of the conceptual model. Once the model is shown to be internally sound, external validation can be attempted.

External validation is the comparison of the capability model to the real world in order to test the external accuracy of the model. If the model is valid, then sensitivity analysis of the model to input parameters can be accomplished.

Plan of Presentation

Through the use of the techniques that have been discussed in this chapter, the present system of determining capability will be studied. This analysis will be presented throughout the next three chapters. In Chapter III the relationships between factors will be studied through a step-by-step development of the causal loop diagram. The importance of this process will be evident in Chapter IV during the development of the system flow diagram and system of equations. Chapter V will contain a sensitivity analysis of the model to determine the effect of management decisions on mission capability.

CHAPTER III

CAUSAL LOOP DESCRIPTION

As stated in Chapter II, the initial understanding of a system can best be attained through a process of causal loop diagramming. In this process interactive factors are shown to be related in a pairwise manner. These pairwise relationships combine to form a complete causal loop diagram of the system. This chapter presents the step-by-step development of such a loop diagram.

In Figure 8 the causal loop diagram describes feedback relationships between available hours, pressure to schedule, number of aircraft scheduled to fly, and number of sorties flown.

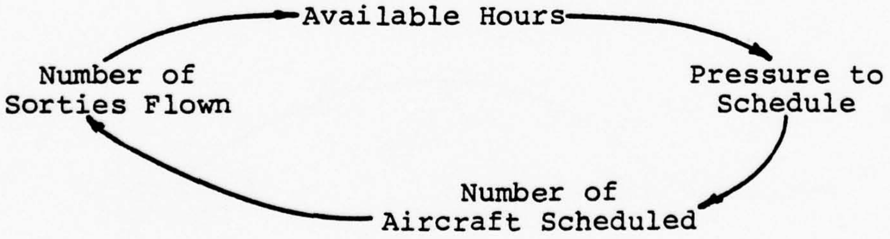


Fig. 8. Scheduling Loop Diagram

This diagram incorporates simple causal hypotheses relating the feedback loop underlying basic system scheduling. These hypotheses include:

1. The number of available flying hours affects the pressure to schedule sorties.

2. A decrease in scheduling pressure will decrease the number of aircraft scheduled.

3. A decrease in the number of aircraft scheduled will lead to a decrease in the number of sorties actually flown.

4. A decrease in the number of sorties flown will cause an increase in the total available hours.

The first relationship, as shown in Figure 9, is that the number of available flying hours affects the pressure to schedule sorties. For example, if available hours are decreased too quickly across a quarter, a perceived pressure to schedule sorties decreases.

Fig. 9. Scheduling Relationship 1

The pressure to schedule drives the next relationship. As the pressure to schedule is decreased, the number of aircraft scheduled to fly is decreased. That is, with less pressure to schedule sorties to fly, fewer aircraft can be used to meet the flying requirements. This relationship is shown in Figure 10.

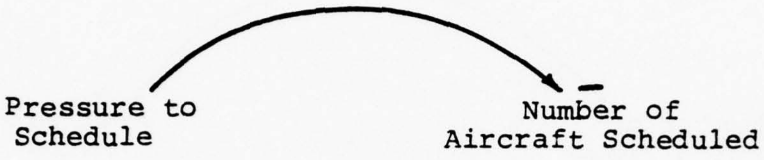


Fig. 10. Scheduling Relationship 2

The third pairwise relationship in this initial causal loop diagram is shown in Figure 11. A decrease in the number of aircraft scheduled leads to a decrease in the number of sorties flown.

Fig. 11. Scheduling Relationship 3

Closing out the feedback loop is the fourth, and possibly less obvious relationship. As the number of sorties flown decreases, the hours remaining available to fly during the period are decreased but at less than the planned rate. This effect is equivalent to an increase in hours remaining available to be scheduled during the rest of the period. This relationship is shown in Figure 12.

Fig. 12. Scheduling Relationship 4

Figure 13 represents the feedback loop portraying the response of scheduled sorties to available flying hours. The negative polarity of the entire loop can be determined by tracing the effect of an arbitrary change in one variable factor. For example, consider the effect of an increase in available flying hours, as might be experienced after a week of reduced flying operations due to adverse weather. This increase in available flying hours causes managers to exert increased pressure upon operations scheduling to schedule additional sorties to fly. The greater number of aircraft scheduled results in more sorties flown which in turn decreases the hours remaining available to fly in the quarter. Thus, the increase in available hours caused by external conditions has led to managerial decisions that eventually reduce the number of available hours.

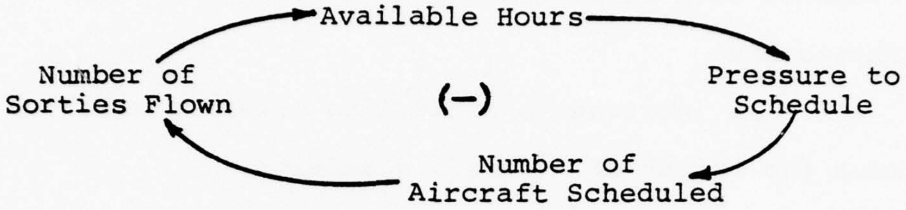


Fig. 13. Scheduling Loop Diagram

Thus, the loop depicts an attempt to maintain an equilibrium position, a characteristic of negative feedback loops.

The second major causal loop diagram, Figure 14, describes the interrelationships between pressure to schedule, number of aircraft scheduled, number of aircraft broken, the amount of maintenance required to fix aircraft, the amount of training available, the percent of skilled personnel, the maintenance capability, and the number of sortie capable aircraft.

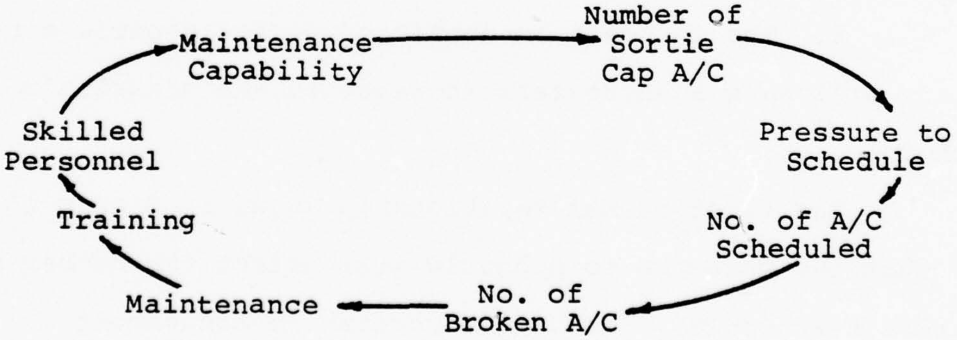


Fig. 14. Maintenance Causal Loop

This diagram incorporates causal hypotheses relating the feedback loop underlying maintenance capability. These hypotheses are:

1. An increase in scheduling pressure will increase the number of aircraft scheduled.

2. The increased aircraft scheduled will increase the number of broken aircraft.

3. A greater number of broken aircraft will affect the level of maintenance performed.

4. More maintenance performed will increase available on-the-job training (OJT).

5. This increased OJT will increase the number of skilled personnel.

6. An increase in skilled personnel will improve maintenance capability.

7. An improved maintenance capability will tend to increase the level of sortie capable aircraft.

8. The increase in number of sortie capable aircraft will have a short-term increase in the pressure to schedule.

The first causal relationship shown in Figure 15 is that the pressure to schedule will affect the number of aircraft scheduled. Thus, an increase in management pressure to schedule more sorties will result in an increase in the number of sorties scheduled.

Fig. 15. Maintenance Relationship 1

The next positive relationship involves number of aircraft scheduled and number of broken aircraft. As an example, if the number of aircraft scheduled increases, then a proportional increase in broken aircraft will appear. This relationship is shown in Figure 16.

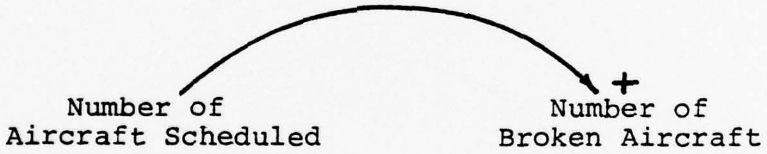


Fig. 16. Maintenance Relationship 2

Figure 17 shows the relationship between number of broken aircraft and maintenance. Thus, as the number of broken aircraft increases, the amount of maintenance required to fix those aircraft will become greater. Therefore, the effect upon the maintenance effort will be directly proportional to the number of broken aircraft.

Fig. 17. Maintenance Relationship 3

The next pair of related factors to be discussed will include maintenance and training. As the amount of maintenance performed becomes greater, then there exists more of an opportunity for training. This is especially true for OJT which can only be accomplished with actual hands-on experience. This relationship between maintenance and training is shown in Figure 18.

Fig. 18. Maintenance Relationship 4

Figure 19 shows the causal relationship between training and skilled personnel. If the amount of training increased so that the time to reach higher skill levels decreased, a surge in skilled personnel would be seen in those critical skill areas. This surge could be directly attributed to the increase in training that certain personnel were receiving.

Fig. 19. Maintenance Relationship 5

The relationship between skilled personnel and maintenance capability is represented in Figure 20. If skilled personnel increased in number, then the actual ability to perform maintenance will also increase. Thus, maintenance capability will be greater when the level of skilled personnel increases. This increased number of skilled personnel will mean that a greater amount of maintenance can be accomplished.

Fig. 20. Maintenance Relationship 6

Figure 21 shows the relationship between maintenance capability and number of sortie capable aircraft. As maintenance capability increases, the number of aircraft considered to be sortie capable would also increase. Thus, a greater capability to perform work will increase the number of available sortie capable aircraft.

Fig. 21. Maintenance Relationship 7

The final causal relationship in this loop is between number of sortie capable aircraft and pressure to schedule. If the number of sortie capable aircraft is increased, then the pressure exerted by most managers increases. This is actually a manifestation of a fear in most managers that an aircraft which is capable of flying, but is not flown, is a lost resource. Thus, if a manager sees an increase in his aircraft resources, a corresponding increase in scheduling pressure will soon follow. These relationships are shown in Figure 22.

Figure 23 represents the feedback loops portraying the response of the eight interrelated factors. The positive polarity of the entire loop can be determined by tracing the consequences of an arbitrary change in one loop variable. For example, consider the effect of an

Fig. 22. Maintenance Relationship 8

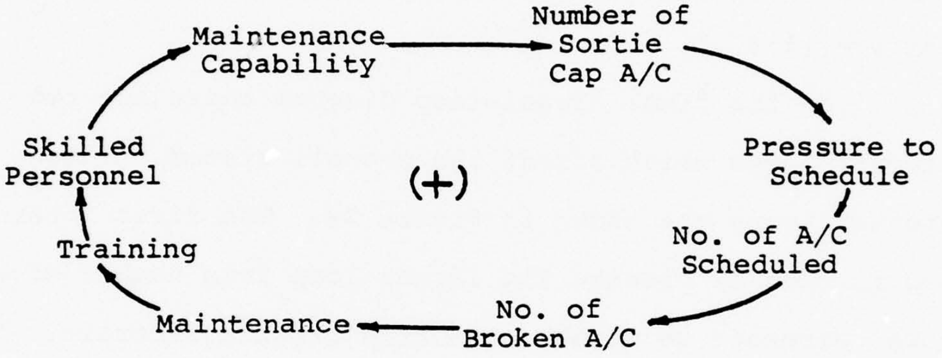


Fig. 23. Maintenance Causal Loop

increase in the pressure to schedule. This increased management pressure to schedule will result in a greater number of aircraft scheduled and thus a greater number of aircraft which will be broken and in need of repair. This increased number of broken aircraft will increase the amount of maintenance performed by technicians. Increasing maintenance will tend to increase the amount of training received by technicians, thus producing more skilled personnel. If a unit has more skilled personnel, then the capability to perform maintenance will be increased. This increased maintenance capability will result in having a greater number of sortie capable aircraft and, therefore, more management pressure to schedule these aircraft. The externally caused increase in pressure to schedule has triggered a set of internal reactions and adjustments in the loop. These changes create pressures which reinforce the original change in pressure to schedule. "When a loop response reinforces the original perturbation, the loop is positive [2:9]."

In the final causal-loop diagram there are two internal loops which affect the overall system. These internal loops are shown in Figure 24. The first internal loop is made by closing the larger loop from number of broken aircraft to number of sortie capable aircraft. Thus, as the number of broken aircraft increases the number of sortie capable aircraft decreases. This decrease in sortie capable aircraft causes a decrease in pressure to schedule. Therefore, the managerial pressure is reduced and the number of aircraft scheduled is decreased. When the number of scheduled aircraft is decreased, then the number of broken aircraft is decreased. Overall, a variable change in the system has resulted in an opposite change to the original perturbation. This is the definition of a negative feedback loop.

The second internal loop is developed by closing the loop between maintenance and maintenance capability and

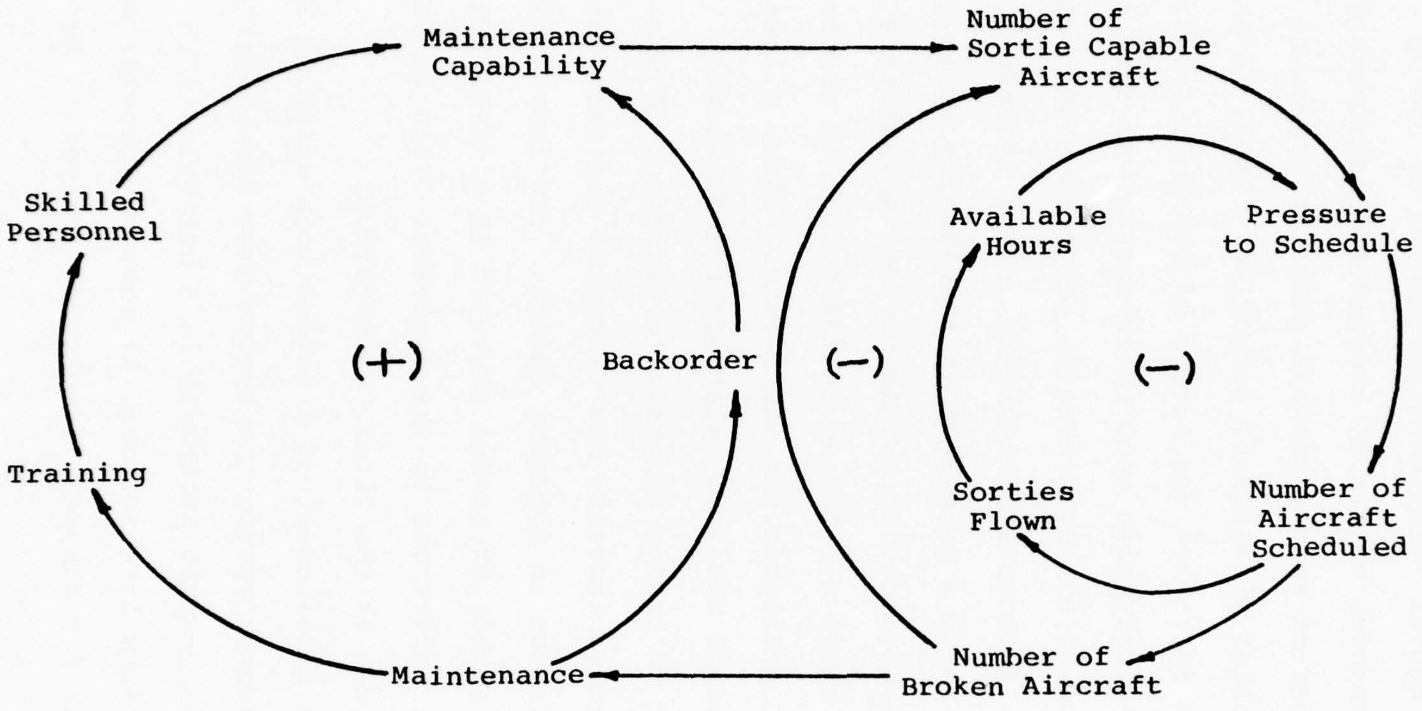


Fig. 24. System Causal Loop Diagram

inserting number of backorders. Thus, the internal loop is composed of the causal relationships: number of broken aircraft, maintenance, number of backorders, maintenance capability, number of sortie capable aircraft, pressure to schedule, and number of aircraft scheduled. Thus, if an external impulse increased the number of broken aircraft, then maintenance would also tend to increase. As more maintenance is performed on the aircraft, the number of backorders which could occur will increase. This increase in backorders will cause a reduction in the ability of maintenance to perform needed work. This reduced maintenance capability will cause a decrease in the number of sortie capable aircraft available for scheduling. Thus, a lower pressure to schedule and fewer aircraft scheduled will cause the number of broken aircraft to decrease. Again, an externally caused increase has triggered the internal reactions which cause an opposing change. The loop attempts to maintain the number of broken aircraft at a fixed level despite external influences to the contrary. This second internal loop, just as the first, is negative.

With the development of a causal loop diagram, the primary relationships within the system have been identified. While this graphic portrayal is a helpful aid in communicating system interactions, it does not provide adequate information for computer simulation analysis. Such analysis is dependent upon a system flow diagram and related system of equations. These will be developed in the following chapter.

CHAPTER IV

SYSTEM FLOW ANALYSIS

The causal loop description presented in the preceding chapter reveals the pairwise interactions within sectors of the system. Such a portrayal is not sufficient, however, to depict or describe adequately the interactions between loops and sensitivity within loops. Yet this total analysis is necessary before a system of equations can be developed for computer simulation. In order to depict the detailed interactions of a system and to provide a transition step to equations, a system flow diagram has been developed. This chapter contains the development of that diagram and the formulation of the system of equations. Prior to presenting this information, however, it is felt that a brief review of symbols and equations used in system dynamics models is needed.

System Flow Diagrams

"Flow diagrams consist of rates, levels, and auxiliary elements organized into a consistent network [2:5]." The graphic symbols used to represent these elements appear in Figure 25. Flow through a system is represented in many ways; three designators used in this chapter are shown in Figure 26.

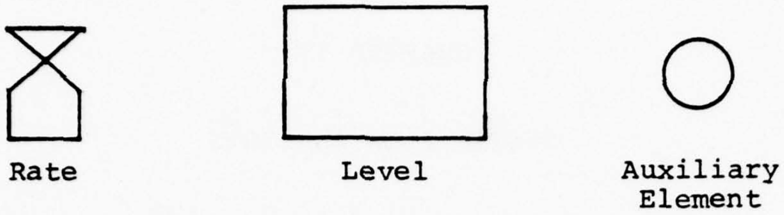


Fig. 25. Basic Element Designators

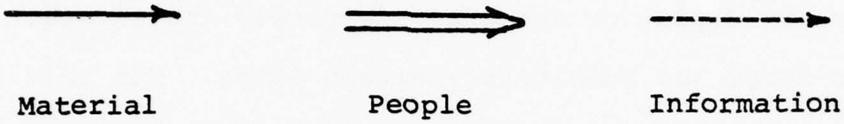


Fig. 26. Flow Designators

The arrowhead shows the direction of flow through the system. Two other important elements in a system flow diagram are the source and *sink for each production line.* These symbols are shown in Figure 27.

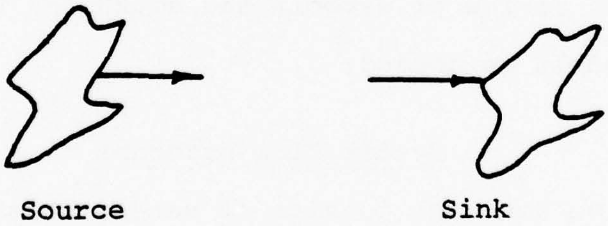


Fig. 27. Source and Sink Designators

Again the arrowhead is important; its direction represents flow out of a source or flow into a sink. The remaining symbol used in this chapter represents constant inputs to the rates, levels, and auxiliary elements described above. A constant input is shown in Figure 28.

Fig. 28. Constant Designator

With these few graphic symbols, all variables within a system can be presented in a flow diagram. The variables in this chapter have been named consistent with their function and a corresponding variable label assigned. For example, a level of sortie capable aircraft has been labeled LOSC; a maintenance rate of repair is ROR. For purposes of clarity and continuity, but at the expense of brevity, the variable name and label will be used together in all narrative descriptions in this chapter. While such duplication may at times seem distracting, it does provide clarity to flow diagram descriptions. With this foundation for flow diagram construction, similar preparation for development of a system of equations is prudent.

System of Equations

In the preceding section the basic structure elements of a system flow diagram were discussed. Such a diagram is the final step in conceptually analyzing a system; it is now time to translate conceptions into a language conducive to computer simulation. This then is the purpose of a system of equations.

Basically, the equation system consists of two types of equations corresponding to the levels and rates discussed above. Other incidental equations support the level and rate equations, but are not so universally used. The several types of equations used later in this chapter will now be discussed. These are equations corresponding to levels, rates, auxiliary elements, TABLE functions, initial values, and constant inputs.

"The level equations show how to obtain levels at time K, based on levels at time J, and on rates over the interval JK [1:75]." A typical level equation from this chapter appears as:

L LOSC.K=LOSC.J+(DT)(ROR.JK-ROB.JK)

The "L" to the left of the equation denotes an upcoming level equation. The equation itself reveals that a level (LOSC) at time K is equal to its level at time J plus the difference in its input (ROR) and output (ROB) over the time interval DT (from J to K). Again, this is the basic form of the level equation; slight variations in structure appear in this chapter, but the purpose of a level equation is preserved.

The inputs and outputs to a level have been mentioned in the discussion of level equations. These factors are represented as rates in a system flow diagram. "The rate equations define the rates of flow between the levels of the system [1:77]." Rates themselves are determined by inputs. A representative rate equation to be seen later follows:

R ROFS.KL=.95*LOSS.K

Again, a single alpha character is used to identify the type of equation ("R" for rate). The equation then relates that some rate (ROFS) over a time period from K to L is equal to 95 percent of a level (LOSS) at time K. In this case a constant value provides one input for the rate.

A constant value requires a much shorter equation than the previous types discussed. One such equation from this chapter illustrates:

C MPROF=.9

The "C" identifies a constant equation in which a constant element labeled MPROF equals 90 percent. Such equations are used often throughout this chapter.

Another commonly used type of equation is the auxiliary equation. True to their name, these equations assist but are incidental; they are often used to break down a rate equation into component equations. Their use reduces complexity of the rate equations and also adds clarity to the meaning of other equations in the model.

Auxiliary equations take many forms in this chapter; an example is presented:

A SDF.K=PULSE(-1,4,4)

The auxiliary equation designator "A" keys the reader and computer to an auxiliary variable. In this case SDF at time K is a PULSE function whereby some rate receives a negative pulse of one unit at time period four and every four time units thereafter. Obviously, this PULSE function could have been made a part of some rate equation, but the separate equation reduces complexity.

Two other types of equations used in this chapter deserve mention. The first, the initial-value equation, is used for each level equation in the system. This equation serves to set an initial value for the level being computed at time K. The initial value equation for LOSC discussed above appears in this chapter as:

N LOSC=4

Thus the initial value of the level LOSC is 4 units. The "N" designates an initial-value equation.

The last type of equation to be discussed is the TABLE function equation. The TABLE function is an auxiliary element that relates one dependent variable to an independent variable through some predetermined pattern (Table). When TABLE is used in an auxiliary equation, that equation must be followed by a second equation giving the TABLE values, the dependent variable values. Such a combination appears as:

```
A  SCHM.K=TABLE(ORAC,LOSC.K,0,5,1)
T  ORAC=0/4/8/13/14/14
```

This set of equations reveals that some auxiliary variable SCHM receives its value at time K from the level LOSC through some TABLE labeled ORAC. In this case, if LOSC.K=3, ORAC=8, and thus SCHM.K=8. This function is a vital tool in system dynamics studies and is used at several key points throughout this chapter.

With this background of the mechanics in the system dynamics language, it is time to proceed into the study at hand. The flow diagrams have been developed around production sectors within the system. These sectors are roughly analagous to the loops in the causal loop diagram developed in the preceding chapter. The first sector to be discussed is the flying hour sector.

Flying Hour Sector

Figure 29 is the flow diagram for the production sector within the system that depicts a quarterly flying hour allocation and reduction of those hours through a weekly flying program. The input to the level of available flying hours (AVHR) is a PULSE of 1400 hours every thirteen weeks. This PULSE represents the quarterly allocation of

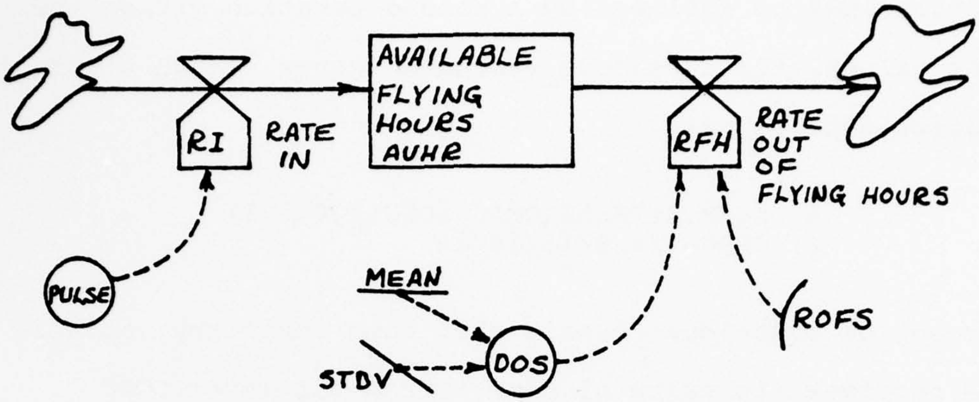


Fig. 29. Flying Hour Sector

flying hours from a major command headquarters to its operational units. The level of available flying hours (AVHR) is reduced as the hours are flown throughout the quarter. This reduction of available flying hours (AVHR) is accomplished through the rate out of flying hours (RFH) which is dependent upon the rate of flying sorties (ROFS) and the duration of those sorties (DOS). The rate of flying sorties (ROFS) will be discussed in a subsequent production sector; the duration of sorties (DOS) is normally distributed with a specified mean (MEAN) of 8 hours/sortie and standard deviation (STDV) of .2 hours/sortie. The following system of equations represents the flow diagram.

```
L   AVHR.K=AVHR.J+PULSE((1400-AVHR),0,13)-(DT)(RFH.JK)
N   AVHR=0
R   RFH.KL=(DOS.K)(ROFS.JK)
A   DOS.K=NORMRN(MEAN,STDV)
C   MEAN=8
C   STDV=.2
```

Planning Sector

The rate at which a unit flies its allocated hours is not constant since it depends upon the two factors mentioned above. As a result, it is possible for a unit to fall behind or get ahead of schedule in its flying of these hours. In order to provide a reference plan for a desired rate, a flow diagram for planned activity is provided. This desired flow of hours is reflected in the flow diagram in Figure 30.

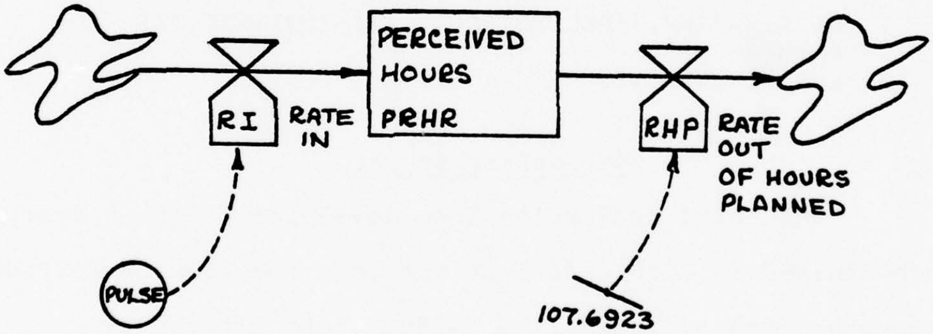


Fig. 30. Planning Sector

The input to the level of perceived hours (PRHR) is the same PULSE of 1400 hours every 13 weeks that was described from Figure 29. The reduction of perceived hours (PRHR) is accomplished in a similar manner; a rate out of hours planned (RHP) drains off the perceived hours (PRHR). The difference in the two flow diagrams is the difference in the rate of hours flown (RHF) and the rate of hours planned (RHP). Since the rate of hours planned (RHP) is a planned expenditure of hours, it can be treated as a constant rate over the weeks of the quarter. That is, the rate of hours planned (RHP) is dependent upon only one value, a constant determined by dividing the magnitude of the PULSE by the thirteen weeks of the quarter. For this research, the magnitude of the PULSE (or quarterly flying hour allocation) was set at 1400; the constant then equals 107.6923. The equations for this part of the system follow:

```
L  PRHR.K=PRHR.J+PULSE(1400,0,13)-(DT)(RHP.JK)
N  PRHR=0
R  RHP.KL=107.6923
```

Scheduling Sector

The third production line developed for this system is contained in Figure 31. It reflects the flow of sorties through a rate of scheduling (ROSCH) into ultimately a sink of sorties flown. The inputs into the rates are slightly more complex as interaction within system elements begins to appear. The input to the level of scheduled sorties (LOSS) is controlled through the rate of scheduling (ROSCH). This rate is determined by a comparison mechanism in system dynamics, a CLIP function. This function compares

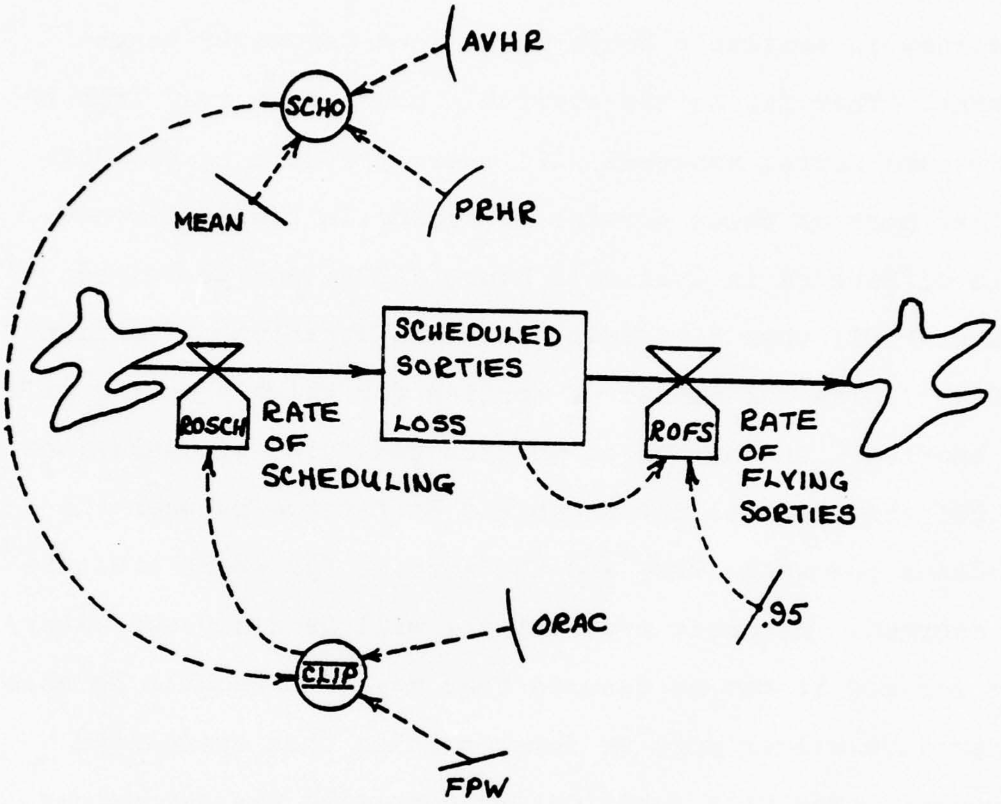


Fig. 31. Scheduling Factor

two inputs and selects one based on the status of the other; in this case the function weighs operational requirements against aircraft availability. Operational requirements in this system are the sorties scheduled by operations (SCHO). This variable consists of a specified fraction per week (FPW) which is the standard number of sorties (13.5) that are scheduled each week and a pressure to schedule additional/fewer sorties that comes from a discrepancy in available hours (AVHR) and perceived hours (PRHR). That is, as the available hours move away from the perceived hours, managers will exert pressure to schedule either more or fewer sorties to reconcile the difference. This difference in available hours (AVHR) and perceived hours (PRHR) when divided by the mean duration of sorties (MEAN) yields the number of sorties for which pressure will be exerted. The number of sorties scheduled by operations (SCHO) then becomes the algebraic difference between the fraction per week (FPW) and the sorties for which pressure is exerted. Aircraft availability will be discussed later, but for now it can be assumed that maintenance will be able to provide either more or fewer sorties than operations requests. The CLIP function, by comparing the two values, insures that the rate of scheduling (ROSCH) does not exceed either the aircraft availability or the operations requirement. The level of scheduled sorties (LOSS) is reduced through a rate of flying sorties (ROFS), a rate established as 95 percent of the sorties scheduled (LOSS). That is, 95 percent of scheduled sorties (LOSS) are flown; the remaining 5 percent are not flown due to ground aborts on the aircraft. The equations for this production line follow:

```
L  LOSS.K=LOSS.J+(DT)(ROSCH.JK-ROFS.JK)
N  LOSS=FPW
C  FPW=13.5
R  ROSCH.KL=CLIP((FPW-SCHO.K),SCHM.K,SCHM.K,(FPW-SCHO.K))
A  SCHO.K=(PRHR.K-AVHR.K)/MEAN
C  MEAN=8
R  ROFS.KL=.95*LOSS.K
```

Maintenance Sector

The fourth production line, as shown in Figure 32, depicts the maintenance sector of the system. Along this path flow a number of aircraft which are repaired, flown, and, as a result of flying, are broken and require maintenance. The rate of repair (ROR) is a complex factor involving several inputs and containing several inherent assumptions. One major assumption is the role of supply in

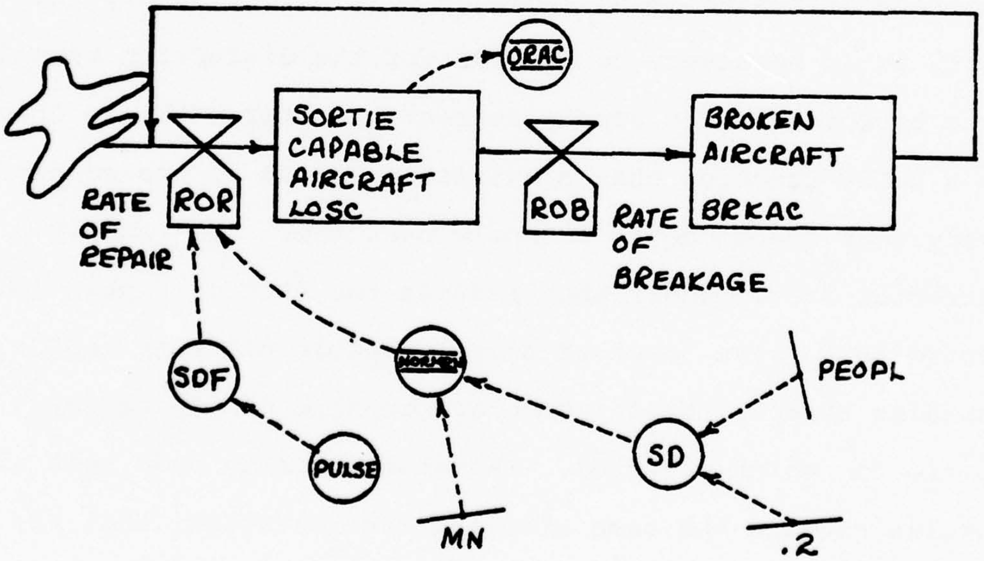


Fig. 32. Maintenance Sector

this variable. A maintenance organization's rate of repair is heavily dependent upon supply's ability to provide the correct parts in a timely manner. An incorrect part or a delay in receiving the correct part adversely affects the rate of repair. Rate of repair (ROR), as used in this system, contains provisions for normal supply support. A second assumption concerns availability of work stations and tools; these factors are included in the mean rate of repair. Rate of repair (ROR) is normally distributed with a specified mean (MN) of fourteen aircraft/week and a standard deviation (SD) partially dependent upon the skill knowledge of the maintenance technicians. This latter factor will be discussed in the next production line. Since the rate of repair (ROR) includes only normal supply support, it is necessary to provide for the disruption caused by a backorder. The supply detractor factor (SDF) is driven by a PULSE function that simulates the loss of one sortie every four weeks due to a supply backorder. The supply detractor factor (SDF) then reduces the rate of repair (ROR) accordingly. The level of sortie capable aircraft (LOSC) contains those aircraft which are capable of flying any sortie for which selected. The assumption is made that all sorties require the same aircraft configuration; that is, either the aircraft can fly or not fly. No provisions are made for special or limited configuration so that certain sorties can be flown. From this level of sortie capable aircraft is taken the information required to determine the number of sorties maintenance is capable of supporting. Through a TABLE function, operationally ready aircraft (ORAC), the number of sortie capable aircraft are converted into sorties that maintenance can support. Recall that it was this support capability that provided the second input into the CLIP function determining the rate of scheduling (ROSCH). The relationship of aircraft to sorties that was used in this TABLE of operationally ready aircraft (ORAC) is shown in Figure 33.

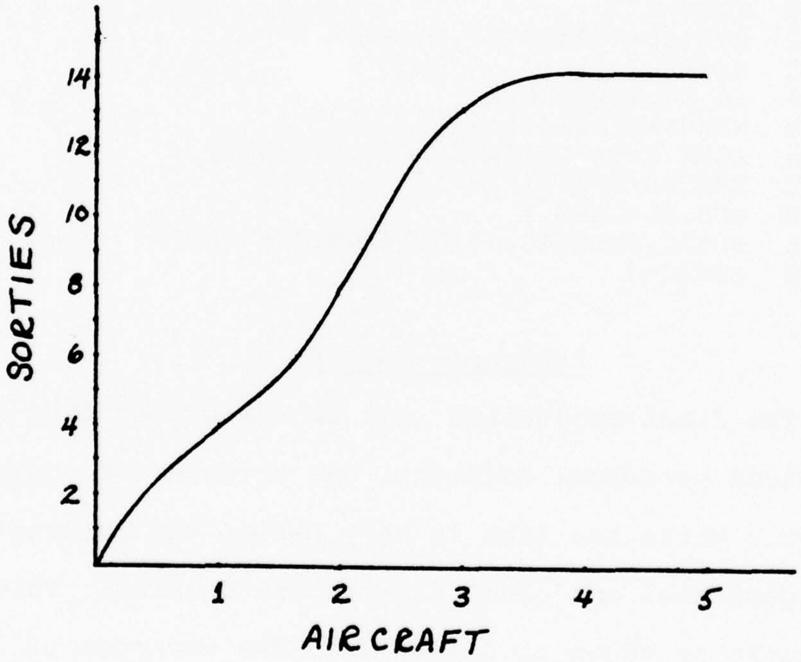


Fig. 33. Operationally Ready Aircraft (ORAC) Table Data

The rate of breakage (ROB) is a direct reflection of the level of scheduled sorties (LOSS); that is, any sortie scheduled results in maintenance requirements. While this relationship may not appear obvious, recall that all sorties scheduled (LOSS) are either flown or result in aborts, either condition requiring maintenance. The rate of breakage (ROB) regulates the flow of aircraft into a level of broken aircraft (BRKAC) which in turn becomes the source of aircraft requiring repair. The system of equations for this production line appears as:

```
L   LOSC.K=LOSC.J+(DT)(ROR.JK-ROB.JK)
N   LOSC=4
R   ROR.KL=NORMRN(MN,SD)+SDF.K
C   MN=14
A   SD.K=.2+PEOPL.K
A   SDF.K=PULSE(-1,4,4)
A   SCHM.K=TABLE(ORAC,LOSC.K,0,5,1)
T   ORAC=0/4/8/13/14/14
R   ROB.KL=LOSS.K
L   BRKAC.K=BRKAC.J+(DT)(ROB.JK-ROR.JK)
N   BRKAC=3
```

Personnel Sector

The final production line in the system flow diagram depicts personnel movement, the turnover of squadron personnel. While the line is very basic, the interactions between personnel and other factors are complex. This relationship is shown in Figure 34. The turnover of squadron personnel (RSQP) falls within a SIN function with period of fifty-two weeks. That is, the inflow and outflow of personnel throughout the year can be represented by a

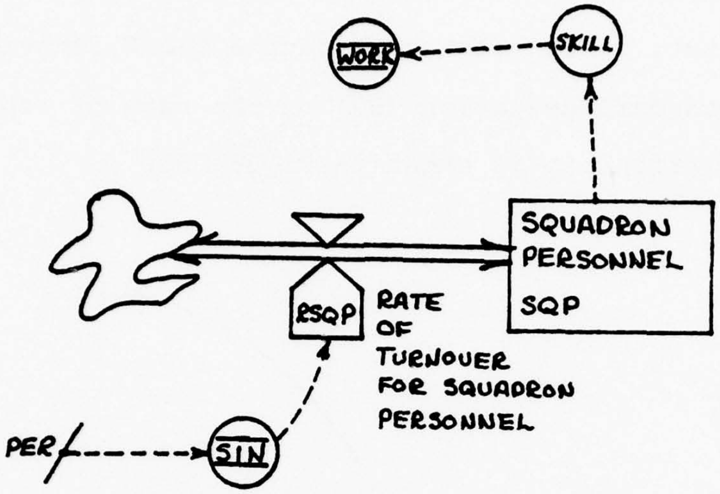


Fig. 34. Personnel Sector

sine curve that flows between 90 percent and 100 percent manning during the year. The peak (100 percent) would occur during the Winter quarter when personnel moves are at a minimum and fall to a low (90 percent) during the Summer quarter when the majority of personnel moves are made. The level of squadron personnel (SQP) is the source of information for the variable function SKILL, or the skill level of squadron personnel. This skill level of squadron personnel (SKILL) is based upon the assumption that 90 percent of the squadron personnel are skilled technicians capable of performing maintenance tasks within their specialty. This 90 percent is reflected through the constant value, maintenance proficiency (MPROF). The variable, skill level of squadron personnel (SKILL), provides the basis for two important interactions with other factors in the system. First, it is related through a TABLE function (WORK) to the standard deviation (SD) of the rate of repair (ROR). This relationship is shown in Figure 35.

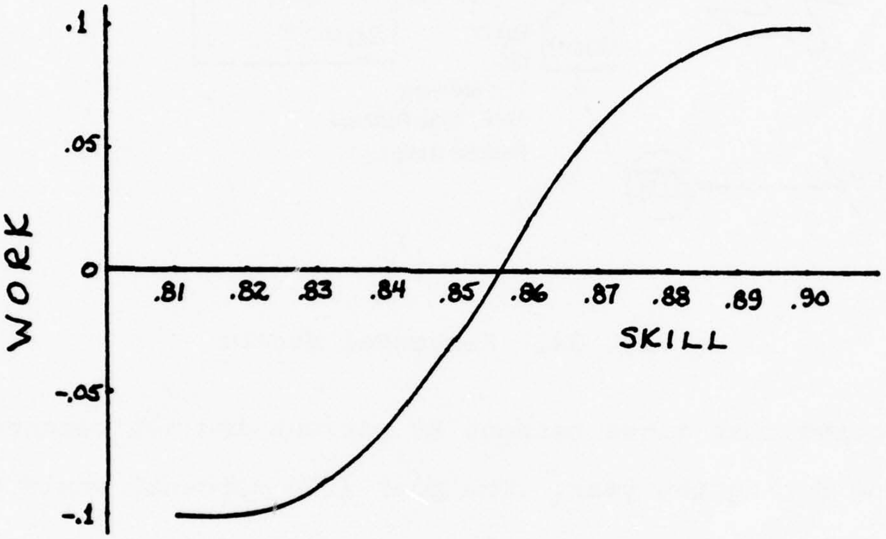


Fig. 35. WORK Table Data

The value corresponding to a given skill level of squadron personnel (SKILL) percentage is added to the constant value .2 to provide the standard deviation (SD) for a rate of repair (ROR). The second function this skill level of squadron personnel (SKILL) performs is to serve as the independent variable for the normal activity designator (NAD) TABLE function. This relationship will be expanded following the equations for the personnel production line:

```
L   SQP.K=(DT)(RSQP.JK)
N   SQP=.95
R   RSQP.KL=(.95+.05*(SIN((6.283*TIME.K)/PER)))/DT
C   PER=52
A   SKILL.K=SQP.K*MPROF
C   MPROF=.9
A   PEOPL.K=TABLE(WORK,SKILL.K,.81,.90,.01)
T   WORK=-.1/-.1/-.09/-.07/-.03/.02/.06/.08/.09/.1
```

Mission Capability Sector

With this last production line, the five sectors of the system have been presented. What remains is to tie these sectors together to reflect their interaction and effect upon mission capability (MISCP). Figure 36 presents the factors and functions found to impact upon mission capability. While it may not pose as neat a picture of the system components as other figures, it is the heart of this system analysis.

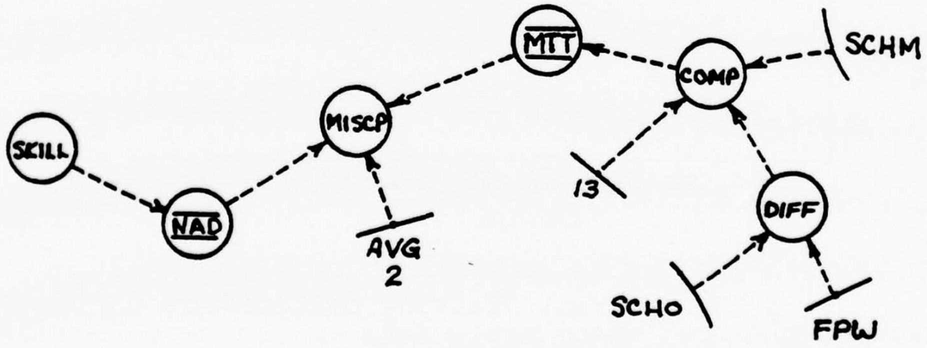


Fig. 36. Mission Capability Sector

Continuing the discussion of the skill level of squadron personnel (SKILL) from the preceding narrative, it provides an input to the normal activity designator (NAD) TABLE. This TABLE function converts the skilled personnel percentage into a percentage value of activity capability. This relationship is shown in Figure 37. The resulting percentage obtained for a particular skill level of squadron personnel (SKILL) percentage becomes one of the inputs into mission capability (MISCP). This input reflects the independent variable men in the original quantification of capability as a function of men, equipment, and management.

Fig. 37. Normal Activity Designator (NAD) Table Data

The equipment variable is synonymous with level of sortie capable aircraft (LOSC), but consideration of the management variable is crucial in measuring the effect of this level upon mission capability (MISCP). Recall for a moment previous discussion of the TABLE function operationally ready aircraft (ORAC). This function was said to translate the level of sortie capable aircraft (LOSC) into the number of sorties maintenance was capable of supporting. This TABLE function then represents the management decisions surrounding equipment. A similar decision process was presented for the number of sorties scheduled by operations (SCHO). Working with these two values can provide an indication of how well a unit performs its daily operations; that is, how nearly is maintenance able to meet the requirements of operations. The variable, difference (DIFF), is used to compare these two values and this value is, in turn, smoothed over the quarter by the SMOOTH function, COMP. The variable COMP then becomes the independent variable for a TABLE function (MTT) which is now a total picture of the maintenance capability expressed as a percentage. This maintenance capability percentage is averaged with the normal activity percentage to yield the mission capability (MISCP) for the system. The data used in the maintenance TABLE (MTT) are shown in Figure 38.

The system of equations for this final part of the flow diagram appears as follows:

```
A   NA.K=TABLE(NAD,SKILL.K,.81,.90,.01)
T   NAD=91/92/93/94/95/96/97/98/99/100
A   DIFF.K=SCHM.K-(FPW-SCHO.K)
A   COMP.K=SMOOTH(DIFF.K,13)
A   MAINT.K=TABLE(MTT,COMP.K,-4,4,1)
T   MTT=60/70/80/90/100/100/100/100/100
A   MISCP.K=(MAINT.K+NA.K)/2
```

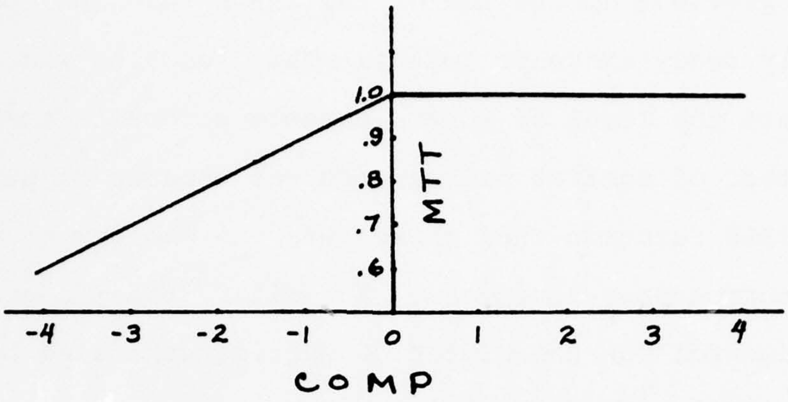


Fig. 38. Maintenance Table (MTT) Data

With the development of the last sector, the analysis of the system flow is complete. All interactions have been portrayed in the flow diagrams and described in the corresponding systems of equations. It remains only to group the individual sectors to form the composite flow diagram which is shown in Figure 39. In a similar manner, the systems of equations are combined and shown in Figure 40. This completes the development of the system model and leads into the performance of a sensitivity analysis, the subject of Chapter V.

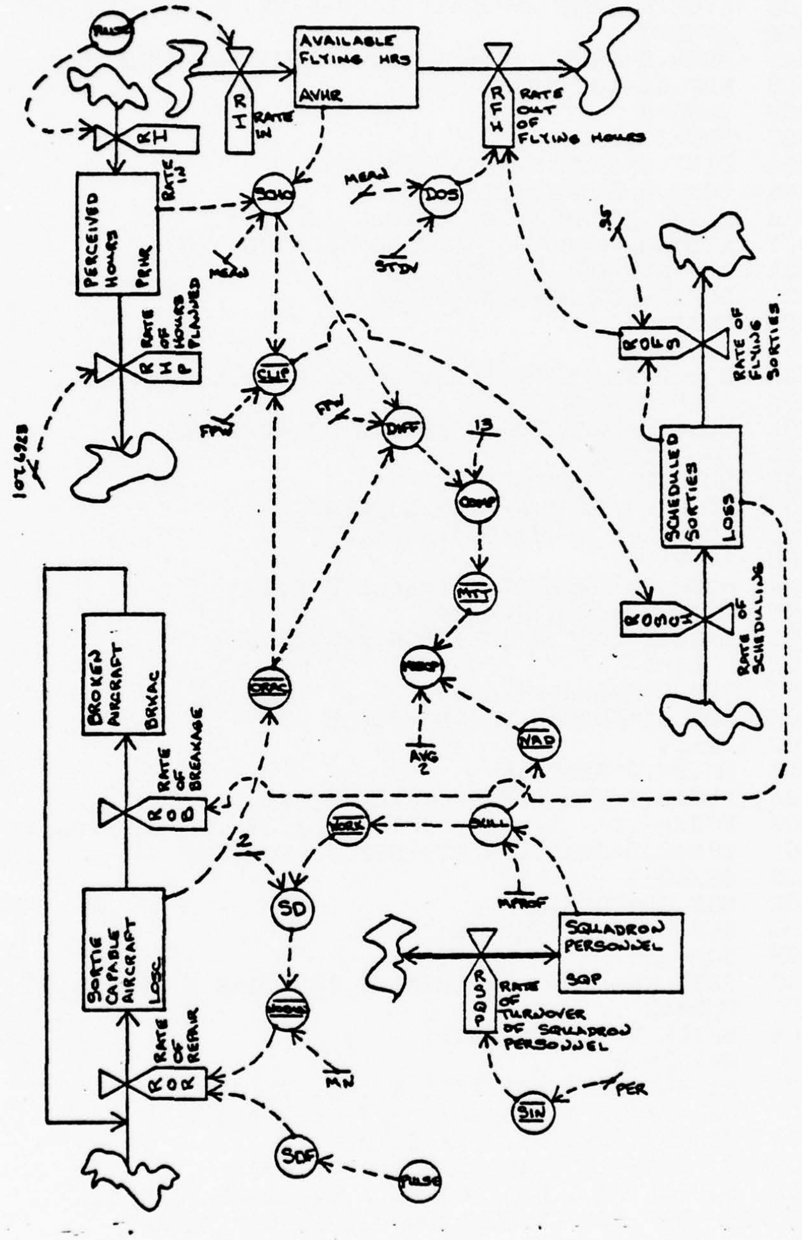


Fig. 39. System Flow Diagram

```
100*   MISSION CAPABILITY MODEL
110L   AVHR.K=AVHR.J+PULSE((1400-AVHR),0,13)-(DT)(RHF.JK)
120N   AVHR=0
130L   PRHR.K=PRHR.J+PULSE(1400,0,13)-(DT)(RHP.JK)
140R   RHP.KL=107.6923
150N   PRHR=0
160C   FPW=13.5
170A   DIFF.K=SCHM.K-(FPW-SCHO.K)
180A   COMP.K=SMOOTH(DIFF.K,13)
190A   MAINT.K=TABLE(MTT,COMP.K,-4,4,1)
200T   MTT=60/70/80/90/100/100/100/100/100
210R   RHF.KL=(DOS.K)(ROFS.JK)
220A   DOS.K=NORMRN(MEAN,STDV)
230C   MEAN=8
240C   STDV=.2
250R   ROSCH.KL=CLIP((FPW-SCHO.K),SCHM.K,SCHM.K,
260X   (FPW-SCHO.K))
270L   LOSS.K=LOSS.J+(DT)(ROSCH.JK-ROFS.JK)
280N   LOSS=13.5
290R   ROFS.KL=.95*LOSS.K
300A   SCHO.K=(PRHR.K-AVHR.K)/MEAN
310L   LOSF.K=LOSF.J+(DT)(ROFS.JK)
320N   LOSF=0
330A   SCHM.K=TABLE(ORAC,LOSC.K,0,5,1)
340T   ORAC=0/4/8/13/14/14
350L   LOSC.K=LOSC.J+(DT)(ROR.JK-ROB.JK)
360N   LOSC=4
370A   SDF.K=PULSE(-1,4,4)
380R   ROR.KL=NORMRN(MN,SD)+SDF.K
390C   MN=14
400A   SD.K=.2+PEOPL.K
410A   PEOPL.K=TABLE(WORK,SKILL.K,.81,.9,.01)
420T   WORK=-.1/-.1/-.09/-.07/-.03/.02/.06/.08/.09/.1
430L   BRKAC.K=BRKAC.J+(DT)(ROB.JK-ROR.JK)
440N   BRKAC=3
450R   ROB.KL=LOSS.K
460L   SQP.K=(DT)(RSQP.JK)
470N   SQP=.95
480R   RSQP.KL=(.95+.05*(SIN((6.283*TIME.K)/PER)))/DT
490C   PER=52
500A   SKILL.K=SQP.K*MPROF
510C   MPROF=.9
520A   NA.K=TABLE(NAD,SKILL.K,.81,.9,.01)
530T   NAD=91/92/93/94/95/96/97/98/99/100
540A   MISCP.K=(MAINT.K+NA.K)/2
550PLOT   AVHR=A(0,1400)/PRHR=P(0,1400)/
560X   SQP=Q(.85,1.05)/LOSC=L(2,6)/MISCP=*(60,100)
570SPEC   DT=.143/LENGTH=208/PRTPER=2/PLTPER=2
```

Fig. 40. System of Equations

CHAPTER V

SENSITIVITY ANALYSIS

In Chapter IV the flow diagram and system of equations were developed, thus accomplishing the objective of designing a system model. This model constitutes a straightforward, understandable description of an aircraft wing's mission capability. Although far too complex in detail for normal mathematical solution, the model makes possible the generation of a specific time linked output that would result if the system were started with specified initial values. This output represents actual operation of a wing over a four-year period as achieved through computer simulation. Such simulation allows analysis of the interactive factors within the system. This sensitivity analysis was performed by changing variables within the system and assessing the effect of those changes upon mission capability. In this chapter an evaluation of the internal validity of the model will be discussed while contrasting the computer output, as shown in the Appendices, to what is actually measured on a daily basis.

The initial computer run was made with the model developed in Chapter IV. Prior to the computer simulation, the confidence in the model rested primarily with the researchers' available knowledge of the system. The computer output supported this confidence when the model exhibited behavior consistent with the behavior of the actual system. This consistency is most obvious in the range of the mission capability results. That is, mission capability, over the four-year period, did not fall below the current standard for "a unit fully capable of performing the mission for which it is organized or designed [3:6A-47]." Experience shows that an operational unit is seldom reported below the standard. With such positive results, the research question concerning model development has been answered. Thus the model can now be used to assess the effect of managerial decisions or parameter changes. Setting the results of the initial computer run, shown in Appendix A, as a baseline measure for system performance, subsequent runs will be evaluated against this basis.

Supply Backorder Adjustment

The first simulation analysis examined the effect of an increase in backorders. Whereas the baseline model provided for one sortie to be lost monthly to backorders, adjustment was made to show the effect of losing four sorties each month. The results of this adjustment are shown in Appendix B. Even though mission capability is adversely affected, the decrease is not so great as might be expected for a four-fold change in the parameter. Also, the mission capability curve over the simulation period maintains roughly the same shape as in the baseline model; however, the range is lowered by about 5 percent at both top and bottom. Another distinctive result of this change is the effect on the level of sortie capable aircraft. The loss of four sorties once a month creates an oscillation that prevents this level from stabilizing.

To further examine the reaction of supply to change, an additional variation in backorders was studied. This variation reflected the loss of four sorties every two weeks. Again the results provided some surprising revelations (Appendix C). While mission capability suffered even more than in the previous run, its curve still retained much of the original shape. Not so surprising was the effect on the level of sortie capable aircraft; the level dropped low, as might be expected, but achieved a much less noticeable oscillation. In fact, by week 160, or after three years, the level appears to have reached a stable value slightly less than 3. This possibly reflects system adaptation to a very deficient, but consistent supply function.

These two analyses were not intended to encompass all the ramifications of supply support. They do provide, however, interesting insight into the effect of backorders on a unit. It has clearly been shown that backorders detract from mission capability, yet this particular area is totally ignored in present capability assessment.

Personnel Proficiency Decrease

In the original model, it was assumed that 90 percent of an organization's personnel resources were skilled technicians. This assumption seemed consistent with experience and, as mentioned above, the model operation lends credence to the assumption. Because of the complex interactions of personnel with other elements of the system, it was felt that this factor deserved further analysis. When maintenance proficiency was dropped from 90 to 80 percent several interesting interactions were exposed, as shown in Appendix D. The effect on mission capability was most evident; this value dropped approximately 5 percentage points all along the curve. The curve itself maintained its original shape, reflecting the direct effect of maintenance proficiency on mission capability. This observation supports a known belief; it is not sufficient that a unit be manned 100 percent, but it is important for that unit to have an adequate percentage of trained technicians. Again this is an area that is not presently measured because only certain critical skill levels are reported.

Maintenance Support for Sorties

One of the key elements in the model as originally conceived was the TABLE function ORAC, a function translating sortie capable aircraft into the number of sorties maintenance was capable of supporting with those aircraft. This is one area of the model definitely affected by managerial decisions, as maintenance schedulers have a good deal of control over this variable. In light of this assumption, it was deemed of interest to examine this TABLE function. In particular, the values in the function were changed to show maintenance able to support more sorties. Whereas previously maintenance could support thirteen sorties with three aircraft and fourteen sorties with four or five aircraft, the TABLE function was changed so that maintenance provided fourteen sorties with three aircraft, fifteen sorties with four aircraft, and seventeen sorties with five aircraft. The results of this change are included in Appendix E.

Upon comparison of the mission capability curves in Appendices A and E, the difference is slight. This is not unreasonable. Maintenance support is vital to mission capability, but only to a point. Once maintenance meets the sortie requirements of operations, it no longer needs to generate additional sorties. This fact is reflected in the model when the CLIP function determines the rate of scheduling. Under the conditions developed in Chapter IV, operations must fly 13.5 sorties each week to meet quarterly flying hour allocations. Under the new TABLE function, maintenance can exceed this demand with only three sortie capable aircraft. For this reason and because of the CLIP function, this change in parameters has very little influence on mission capability.

Rate of Repair Variation

The final variable that was examined in this sensitivity analysis was the maintenance rate of repair, specifically the standard deviation of that normally distributed rate. Originally, the constant part of this standard deviation was established at .2 sorties/week, but Appendix F contains the results of a change to .5 sorties/week. The change in mission capability is hardly discernible. Possibly more worthy of comment is the slight decrease in the level of sortie capable aircraft.

The purpose of a sensitivity analysis is to highlight those factors within a system that have the greatest effect upon system performance. As Jay W. Forrester has said, "A system . . . is insensitive to changes in most of the equation parameters [1:268]." By knowing those factors that produce a change and by knowing the direction of change, a manager can more accurately make decisions consistent with the goals of the organization. This knowledge can come through the sensitivity analysis afforded by a system dynamics model.

With the results of the sensitivity analysis, the goals for this chapter have been met. The model has been shown to be internally valid and several of the more important parameters within the system identified. It is appropriate at this time to reflect back over the last several chapters. Chapter VI will contain a summarization of these chapters and recommendations for possible further research.

CHAPTER VI

SUMMARY

Mission capability assessment is a vital information-feedback system within the Air Force and Department of Defense. The daily reports are used both for day-to-day management and for long-term planning. As a result of this important role, mission capability assessment must be made as accurately as possible. Yet, to this day, static measurement systems are used for a system composed of dynamic interactions. This method ignores the available technology for assessing complex systems.

System dynamics is a simulation technique that has been used with success in modeling complex systems in the civilian sector. It was the intent of this research effort to apply that technique to the system of mission capability assessment. To guide the research, three objectives were identified; the overall objective being to design and operate a model of the present system that determines an aircraft wing's mission capability.

To achieve this latter objective, an understanding of the system was built around causal-loop diagrams and system flow diagrams. While these two graphic descriptions provided logic for further analysis, they were not sufficient for computer simulation inputs. As a final step to the understanding phase of the research, a system of equations was developed. These equations quantified the previous diagrams and made possible computer simulation. Through refinement, they became the model that was part of the research objective.

The final phase of the research objective was fulfilled when the model was exposed to computer simulation.

> The model then takes the place of the real system and simulates its operation under circumstances that are as realistic as was the original description of the system [1:44].

This simulation provided insight into the interaction, identifying the impact of many management decisions and changing parameters on a unit's mission capability. This is equivalent to trying a new policy or organizational structure in the real system, but here the cost is insignificant compared with the cost of real-life experiment.

Simulation provided the results analyzed in Chapter V. In some cases, the effect on mission capability was intuitive, but in others, counterintuitive. This counterintuitive behavior can be identified only through a dynamic analysis; otherwise, it goes unmeasured. This is exactly the deficiency in present capability measurement systems.

The research plan for this thesis has been met; the model has been shown to be internally valid; it is indeed representative of the real world. Time constraints prohibit further validation in this thesis. Thus, external validation is left for future research efforts.

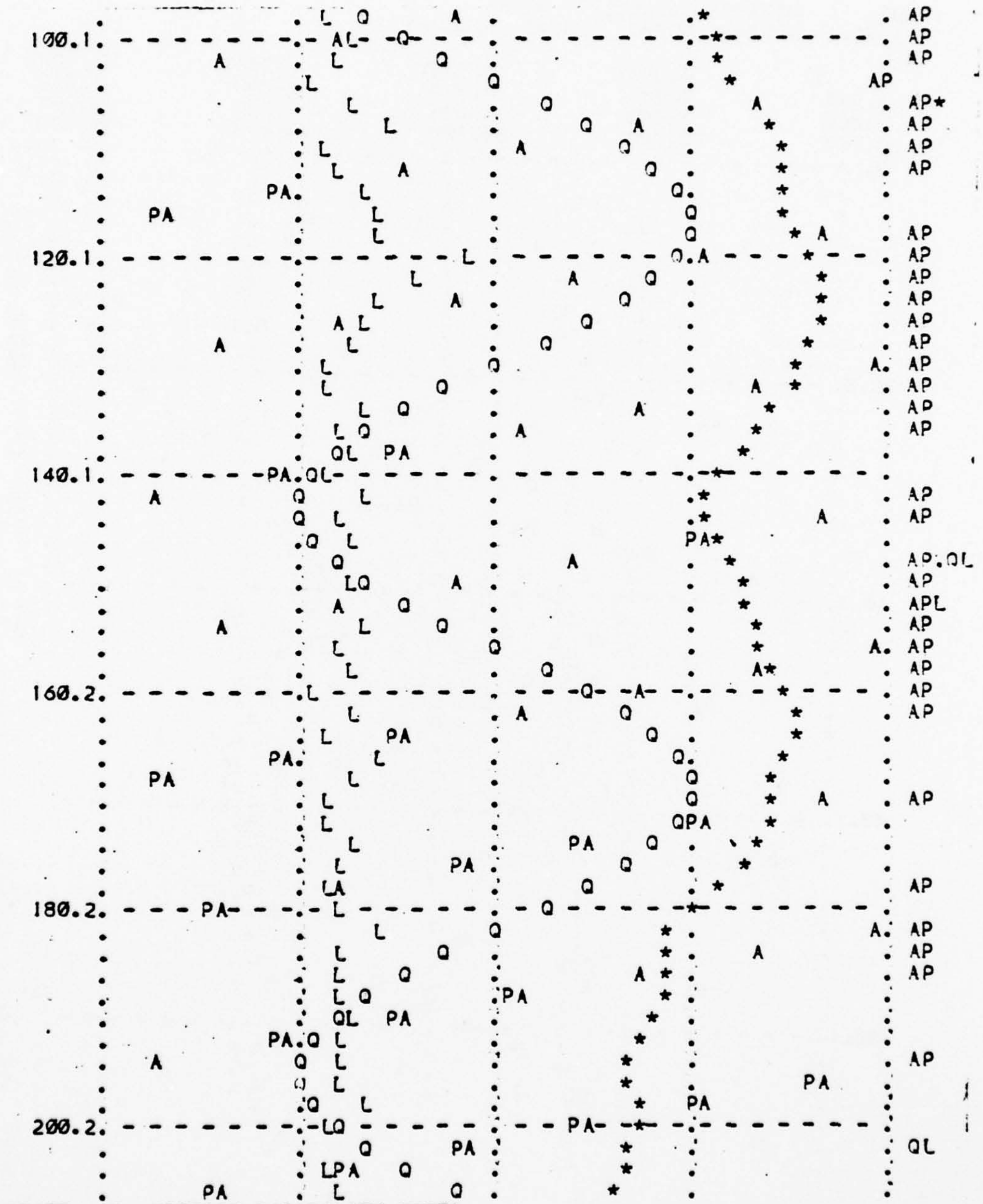
APPENDICES

APPENDIX A

BASIC MODEL SIMULATION

```
1PAGE   1  MISSION CAPABILITY MODEL
   AVHR=A  PRHR=P  SQP=Q  LOSC=L  MISCP=*

     0.   T              0.350T              0.700T              1.050T              1.400T AP
      0.850               0.900               0.950               1.000               1.050  Q
      2.000               3.000               4.000               5.000               6.000  L
     60.000              70.000              80.000              90.000             100.000  *
       0. A - - - - - - - - - . - - - - - - - - - Q - - - - - - - - - . - - - - - -  -*-  . AP.QL
          .                   .                   .L  Q               .       A       *   . AP
          .                   .      L            .        Q    AP    .                *  .
          .                   .L                  .  A         Q      .                  *. AP
          .                   .    L    A         .               Q   .                  *. AP
          .                  A.      L            .                  Q.                   * AP
          .     A             .L                  .                   Q                  *. AP
          .                   .       L           .                   Q             PA *  .
          .                   .       L           .                  Q.A              *   . AP
          .                   .    L              .        A   Q      .              *    . AP
      20.0. - - - - - - - - - .-    L - - - -  A  . - - - - -  Q - - -. - - - - - -*- - - . AP
          .                   .   PAL             .        Q          .          *        .
          .           PA      .          L        .    Q              .       *           .
          PA                  .  L                Q                   .   *               .
          .                   .      L        Q   .                   .   *   A           . AP
          .                   .      L   Q        .              PA   .  *                .
          .                   .      Q            .  PA               *                   . QL
          .                   .   Q      PA       .                *  .                   . QL
          .                  PAQ     L            .              *    .                   .
          .    P  A           Q     L             .           *       .                   .
      40.0. - - - - - - - - --Q- -   -L- - - - -  . - - - - - *- - - -. - - - - - --A- -  . AP
          .                   .Q     L            .             *     .A                  . AP
          .                   .   Q   L           .         A    *    .                   . AP
          .                   .     LQ        PA  .               *   .                   .
          .                   .   PAL    Q        .                *  .                   .
          .           PA      .      L       Q    .                *  .                   .
          A                   .   L               Q                  *.                   . AP
          .                   .      L            .   Q               *       A           . AP
          .                   .         L         .         Q    PA   .*                  .
          .                   .  L                .  PA         Q     .*                  .
      60.1. - - - - - - - - - .-  - -L- -PA - -   . - - - - - - - Q - .* - - - - - - - -  .
          .                  PA      L            .                  Q*                   .
          .    P  A           .       L           .                *  Q                   .
          .                   .       L           .                *  Q             A     . AP
          .                   .     L             .                  Q.A                  . AP.Q*
          .                   .     L             .         A     Q  *.                   . AP
          .                   .     L          PA .             Q    *.                   .
          .                   .   PAL             .         Q      *  .                   .
          .            PA     .   L               .     Q         *   .                   .
          .                   .      L            Q             *     .                  AP
      80.1. - - - - - - - - - . - - - - -  -L-Q-  . - - - - - - - * - .- -   A - - - - -  . AP
          .                   .      L   Q        .              A *  .                   . AP
          .                   .  L   Q            .  A               *.                   . AP
          .                   .   QL     A        .                *  .                   . AP
          .                 PA.Q  L               .                *  .                   .
          .     PA            Q     L             .              *    .                   .
          .                   Q     L             .               * . .             A     . AP
          .                   .Q         L        .                  *.A                  . AP
          .                   .  LQ               .       PA          *                   .
          .                   .  L   Q        A   .                   .*                  . AP
     100.1. - - - - - - - - - .- -   AL- -Q- - -  . - - - - - - - - - . -*- - - - - - -   . AP
          .           A       .   L          Q    .                   .  *                . AP
```



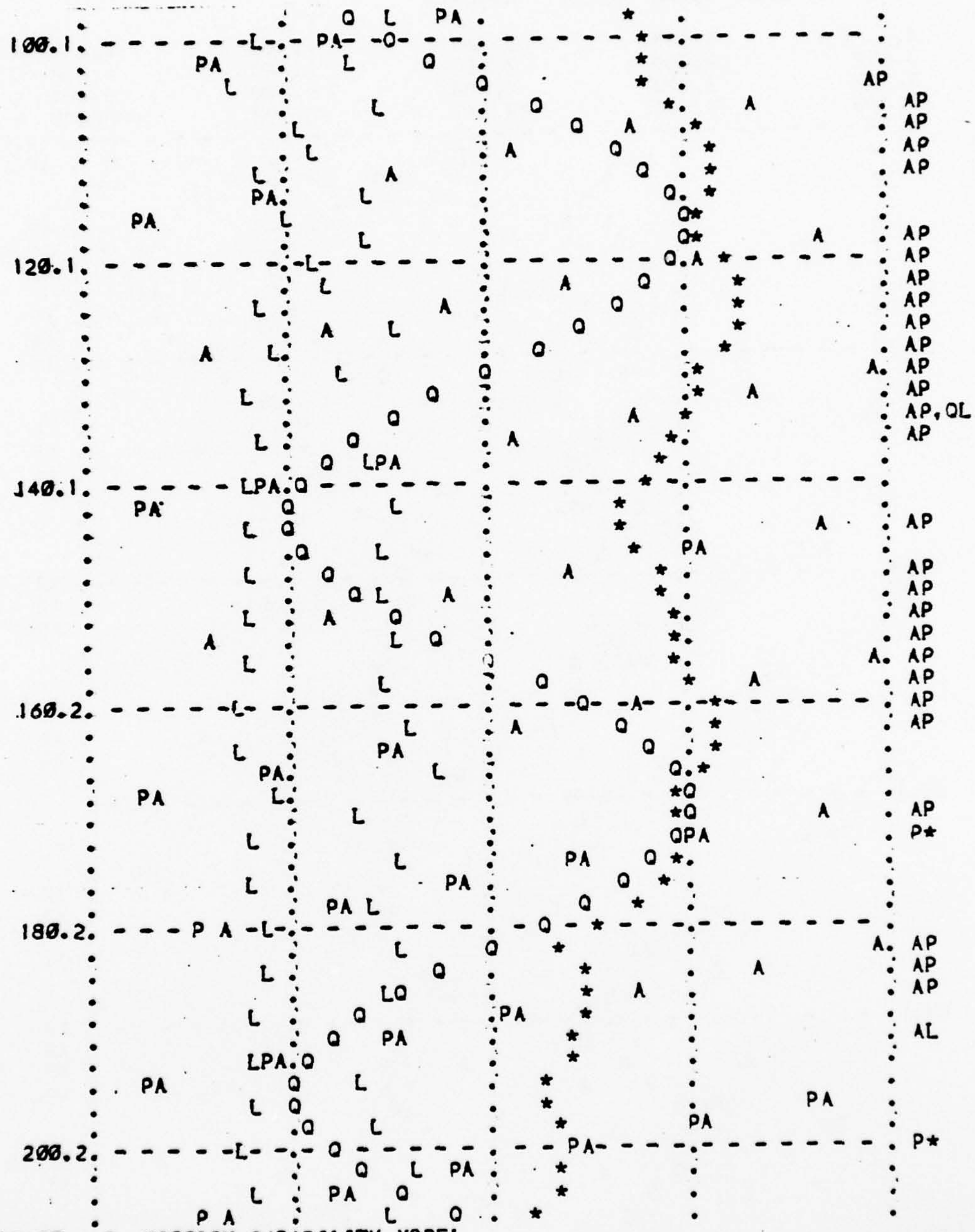
1PAGE 2 MISSION CAPABILITY MODEL

APPENDIX B

FIRST SUPPLY BACKORDER SIMULATION

```
1PAGE   1  MISSION CAPABILITY MODEL
 AVHR=A  PRHR=P  SQP=Q  LOSC=L  MISCP=*

   0.    T       0.350T           0.700T         1.050T         1.400T AP
   0.850          0.900           0.950          1.000          1.050  Q
   2.000          3.000           4.000          5.000          6.000  L
  60.000         70.000          80.000         90.000         100.000  *
    0. A - - - - - - -. - - - - - - -Q - - - - - - -.- - - - - -*- . AP.QL
       .              .              .L Q           .     A     *  . AP
       .              .    L         .      Q   AP  .            * .
                      .      L       .  PA     Q    .             *.
       .              .    L  A      .           Q  .             *. AP
       .             A.       L      .             Q.           *  . AP
       .    A         . L            .              O          *   . AP
       .              .            L .              Q        *PA   .
       .              .      L       .             Q.A       *     . AP
       .              .  L           .      A  Q    .       *      . AP
   20.0. - - - - - - -. - -L- - - -A . - - - - Q - -. - * - - - - . AP
       .              .  PA    L     .      Q       .   *          .
       .        PA    .        L     .   Q          .*             .
       PA             .   L          Q            * .              .
       .              .     L     Q  .            * .     A        . AP
       .              .      LQ      .          PA  .              . A*
       .              .    QL        . PA       *   .              .
       .              .  Q   LPA     .        *     .              .
       .            PAQ     L        .      *       .              .
       .   P A        Q     L        .   *          .              .
   40.0. - - - - - - -Q - - - L - - - . -*- - - - - -. - - - - A- - . AP
       .              .Q     L       .    *         .A             . AP
       .              .  Q   L       .      A       .              . AP*
       .              .    QL     PA .      *       .              .
       .              .  PA L Q      .       *      .              .
       .        PA    .       L  Q   .       *      .              .
       PA             .    L         Q       *      .              .
       .              .         L    .  Q     *     .     A        . AP
       .              .       L      .      Q   PA  .              . P*
       .              . L            . PA      Q*   .              .
   60.1. - - - - - - -. - --L-PA - . - - - - * Q -. - - - - - - -.
       .             PA       L      .        *    Q.              .
       .   P A        .      L       .      *       Q              .
       .              .       L      .     *        Q         PA   .
       .              .    L         .       *     Q.A             . AP
       .              .         L    .      A*   Q  .              . AP
       .             L.           PA .       * Q    .              .
       .              .  PA L        .      Q       .              . Q*
       .        PA  L .              .   Q*         .              .
       .              .     L        Q  *           .             AP
   80.1. - - - - - - -. - --L- - -Q- . - - * - - - -. - -A - - - - . AP
       .              .   L   Q      .      *   A   .              . AP
       .          L   .    Q         . A     *      .              . AP
       .              .  Q    A      .       *      .              . APL
       .           LPA.Q             .      *       .              .
       .   PA         Q     L        .    *         .              .
       .              Q              .     *        .         A    . AP.QL
       .              .Q     L       .        *     .A             . AP
       .          L   .  Q           .     PA   *   .              .
       .              .    Q  L   PA .          *   .              .
  100.1. - - - - - -L-.- PA- -Q- - - . - - - - - * -. - - - - - - -.
       .        PA    .    L     Q   .           *  .              .
```



1PAGE 2 MISSION CAPABILITY MODEL

APPENDIX C

SECOND SUPPLY BACKORDER SIMULATION

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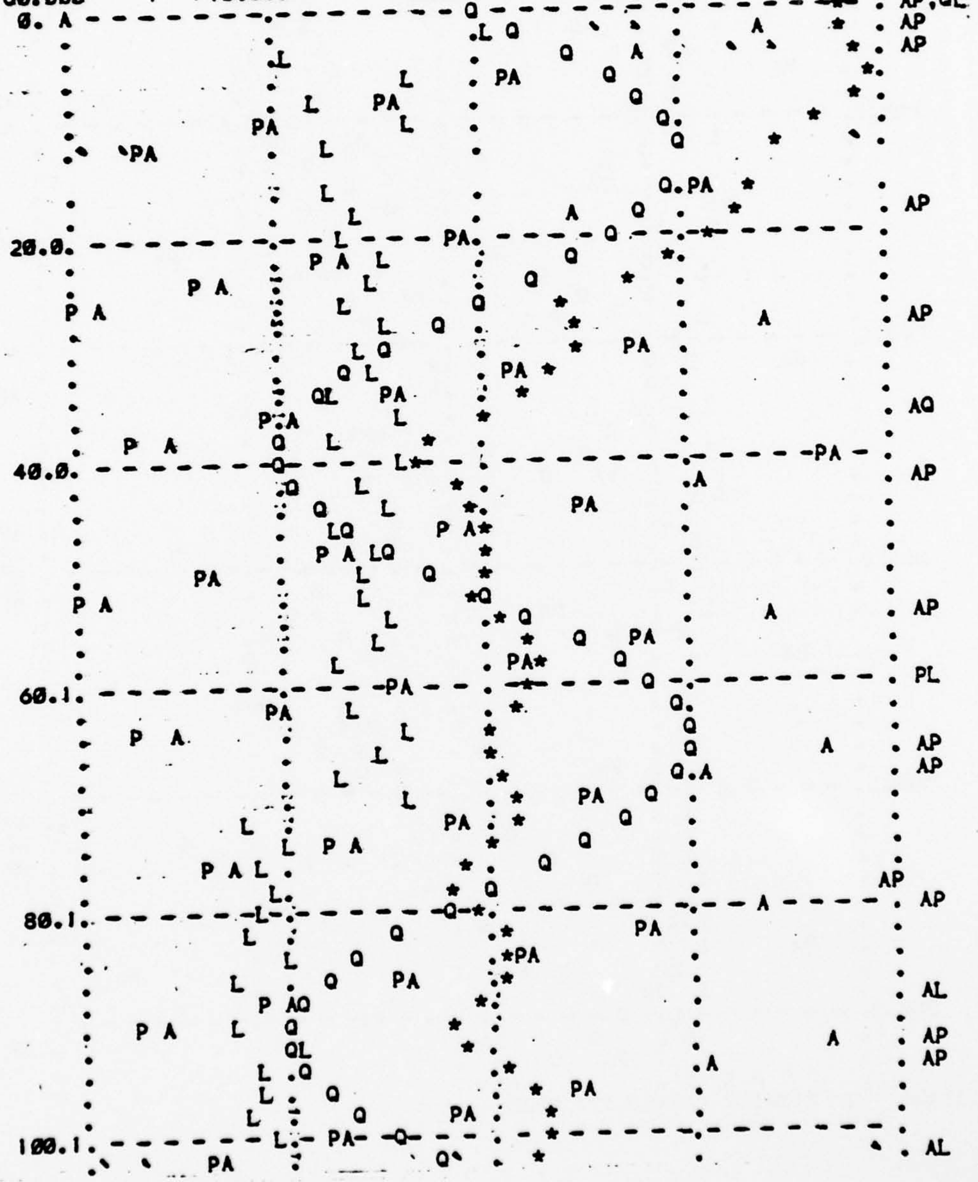
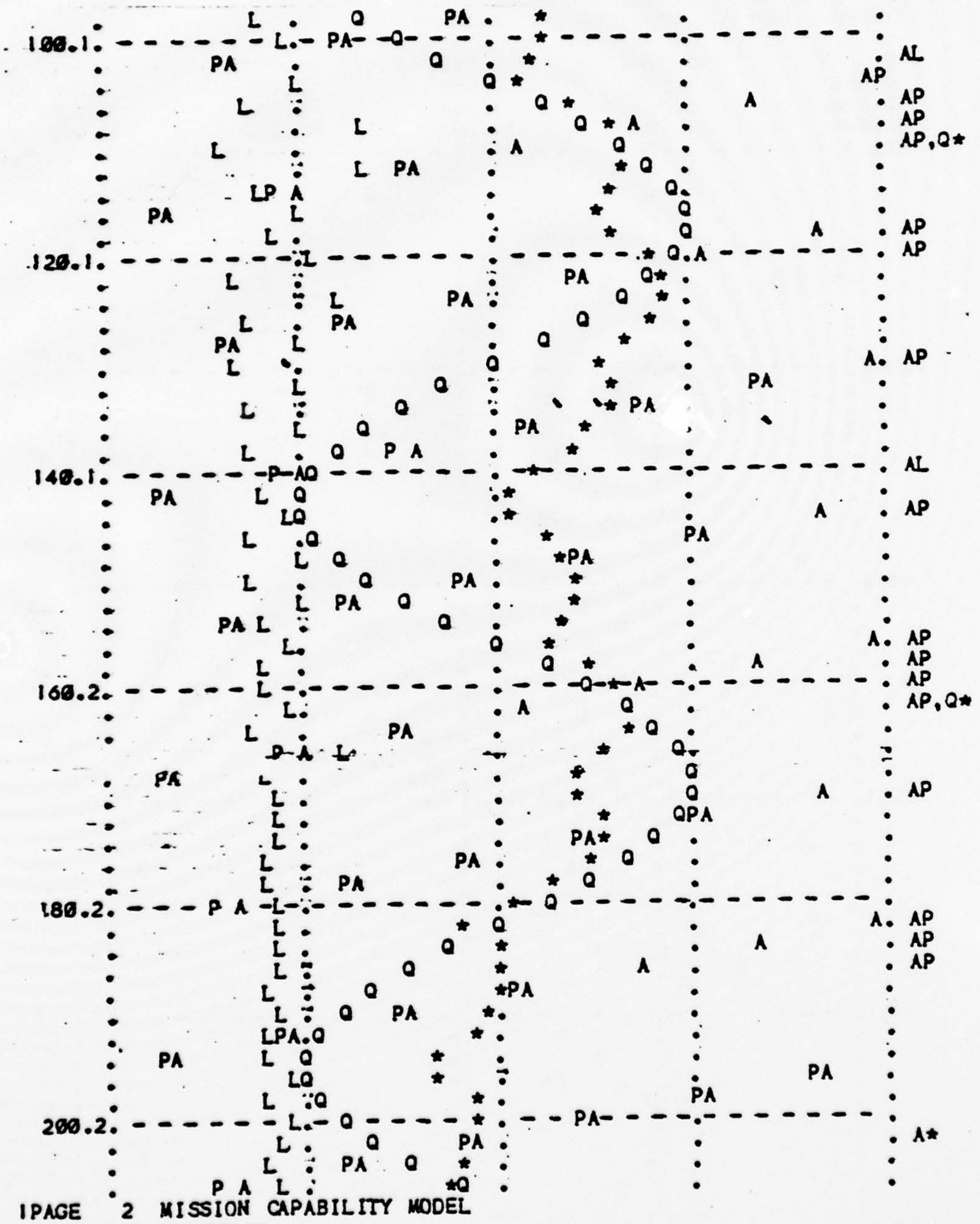
    0.850              0.900             0.950             1.000             1.050   Q
    2.000              3.000             4.000             5.000             6.000   L
   60.000             70.000            80.000            90.000           100.000   *
```





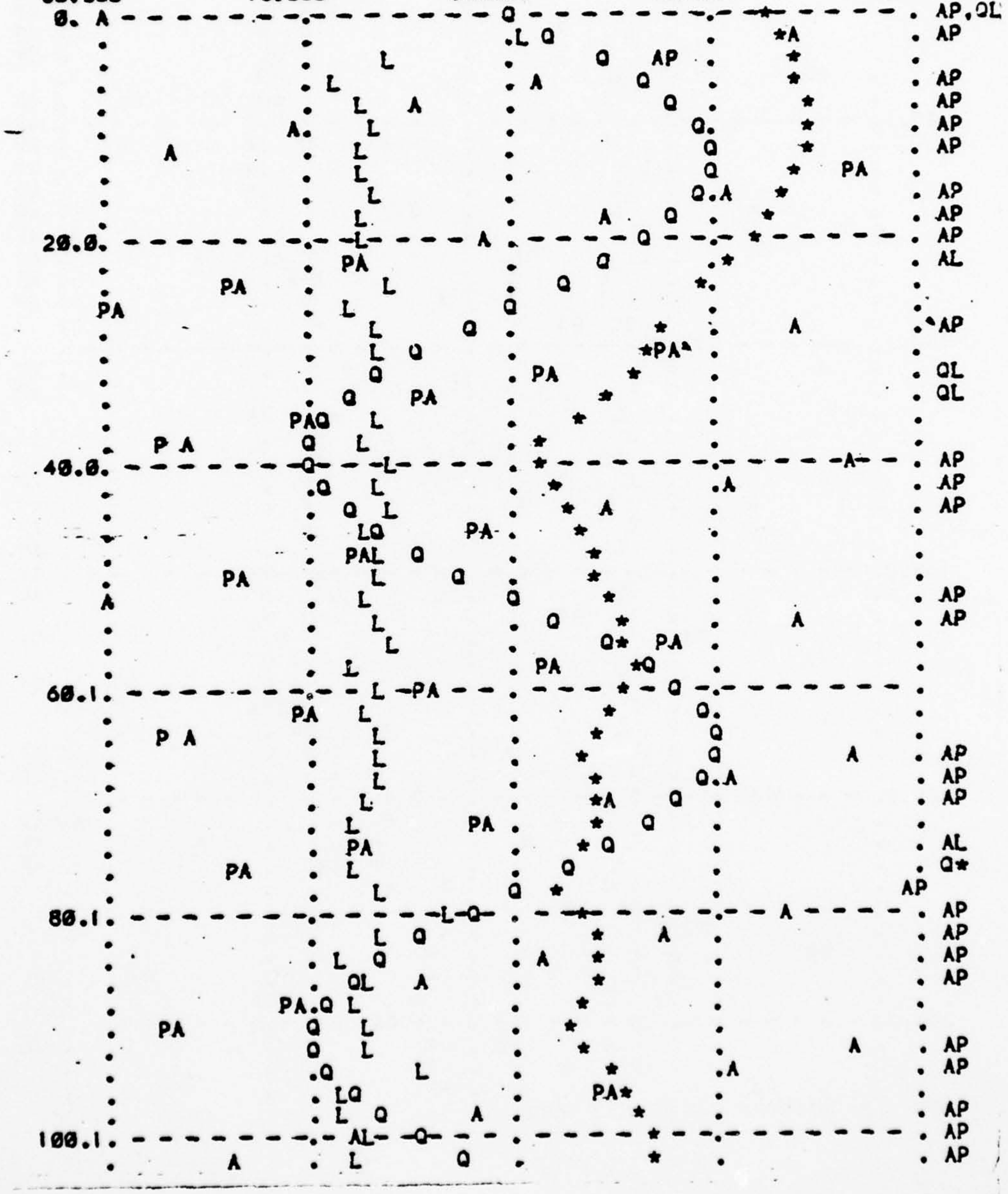
IPAGE 2 MISSION CAPABILITY MODEL

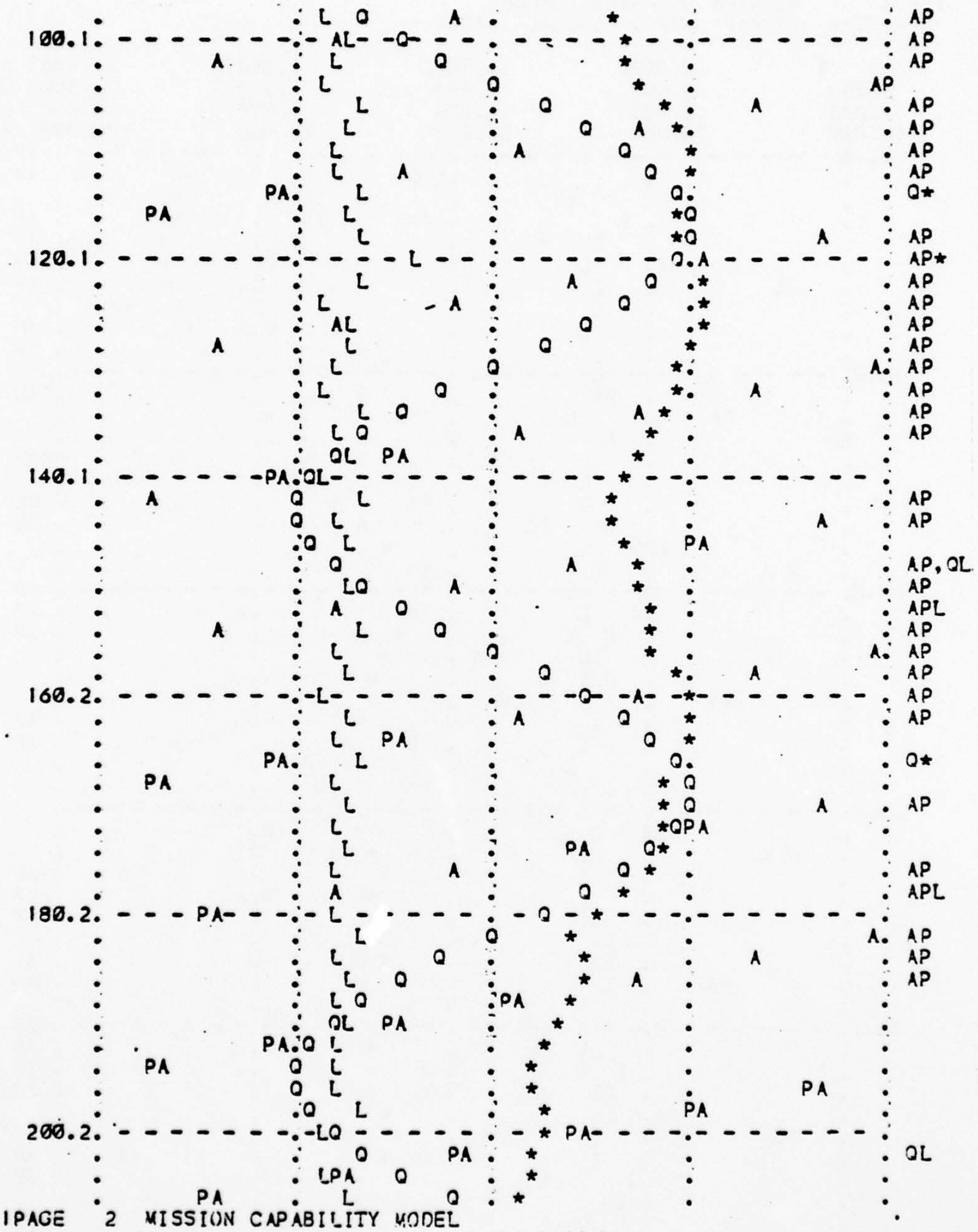
APPENDIX D

PERSONNEL PROFICIENCY SIMULATION

```
1PAGE   1  MISSION CAPABILITY MODEL
   AVHR=A  PRHR=P  SOP=Q  LOSC=L  MISCP=*

   0.    T          0.350T          0.700T          1.050T          1.400T AP
   0.850            0.900           0.950           1.000           1.050  Q
   2.000            3.000           4.000           5.000           6.000  L
  60.000           70.000          80.000          90.000         100.000  *
```





1PAGE 2 MISSION CAPABILITY MODEL

APPENDIX E

MAINTENANCE SUPPORT SIMULATION

```
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   AVHR=A  PRHR=P  SQP=Q  LOSC=L  MISCP=*

   0.    T                0.350T             0.700T              1.050T              1.400T AP
    0.850                0.900               0.950              1.000               1.050  Q
    2.000                3.000               4.000              5.000               6.000  L
   60.000               70.000              80.000             90.000             100.000  *
    0. A - - - - - - - - - . - - - - - - - - - Q - - - - - - - - - . - - - - - - - * - . AP,QL
       .                   .                   .L Q                .       A      *    . AP
       .                   .     L             .        Q    AP    .                *  .
       .                   L                   . A          Q      .                 * . AP
       .             L     .         A         .              Q    .                 * . AP
       .                  A.L                  .                  Q.                   * AP
       .     A             .    L              .                   Q                   * AP
       .             L     .                   .                   Q            A      * AP
       .                   . L                 .                  Q.A                  * AP
       .                L  .                   .        A      Q   .                  *. AP
   20.0. - - - - - - - - L . - - - - - - - -A- . - - - - - -Q- - - . - - - - - - - - -*. AP
       .                  L.   PA              .        Q          .               *   .
       .           PA      L                   .    Q              .            *      .
       P A                L.                   Q                   .        *          .
       .                L  .               Q   .                   .       A           . AP*
       .                   L         Q         .             PA    .     *             .
       .                   L     Q             . PA                .   *               .
       .                L  .   Q     PA        .                   .*                  .
       .                  PAQ                  .                  *.                   . AL
       .     P A           Q                   .             *     .                   . QL
   40.0. - - - - - - - - -LQ - - - - - - - - - . - - - - - - * - - . - - - - - -A- - - . AP
       .                  L.Q                  .               *   .A                  . AP
       .                  L.   Q               .        A       *  .                   . AP
       .                   L      Q         PA .                *  .                   .
       .                  L.    PA   Q         .                *  .                   .
       .            PA L   .              Q    .                  *.                   .
       P A                L.                   Q                  *.                   .
       .                   .L                  .   Q               *       A           . AP
       .                   .L                  .        Q    PA    .*                  .
       .                L  .                   . PA         Q      .*                  .
   60.1. - - - - - - -L- - . - - - - PA- - - - . - - - - - - - Q - .*- - - - - - - - - .
       .                  PA  L                .                  Q*                   .
       .     P A        L  .                   .                  *Q                   .
       .                  L.                   .                  *Q            A      . AP
       .                   L                   .                  Q.A                  . AP,Q*
       .                   .L                  .        A      Q   *                   . AP
       .               L   .                PA .            Q     *.                   .
       .               L   .    PA             .        Q         *.                   .
       .           PA      L                   .    Q           *  .                   .
       .                   .L                  Q             *     .                  AP
   80.1. - - - - - - - - - . - - - - L - - Q - . - - - - - - - - -*. - - -PA - - - - - .
       .              L    .          Q        .              A    *                   . AP
       .                   L      Q            . A                 *                   . AP
       .                   L   Q      A        .                  *.                   . AP
       .           L     PA.Q                  .                  *.                   .
       .     PA           LQ                   .                *  .                   .
       .                  LQ                   .                *  .            A      . AP
       .                  L.Q                  .                   *A                  . AP
       .                  L.   Q               .       PA          .*                  .
       .                  L.      Q         PA .                   .*                  .
  100.1. - - - - - - L - - . - A - - -Q- - - - . - - - - - - - - - . * - - - - - - - - . AP
       .           A      L.              Q    .                   . *                 . AP
```

AD-A059 545   AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OHIO SCHO--ETC   F/G 15/3
A SYSTEM DYNAMICS STUDY OF THE FACTORS USED IN THE MEASUREMENT --ETC(U)
JUN 78   B G FITZGERALD, P E MILLER

UNCLASSIFIED   AFIT-LSSR-23-78A   NL

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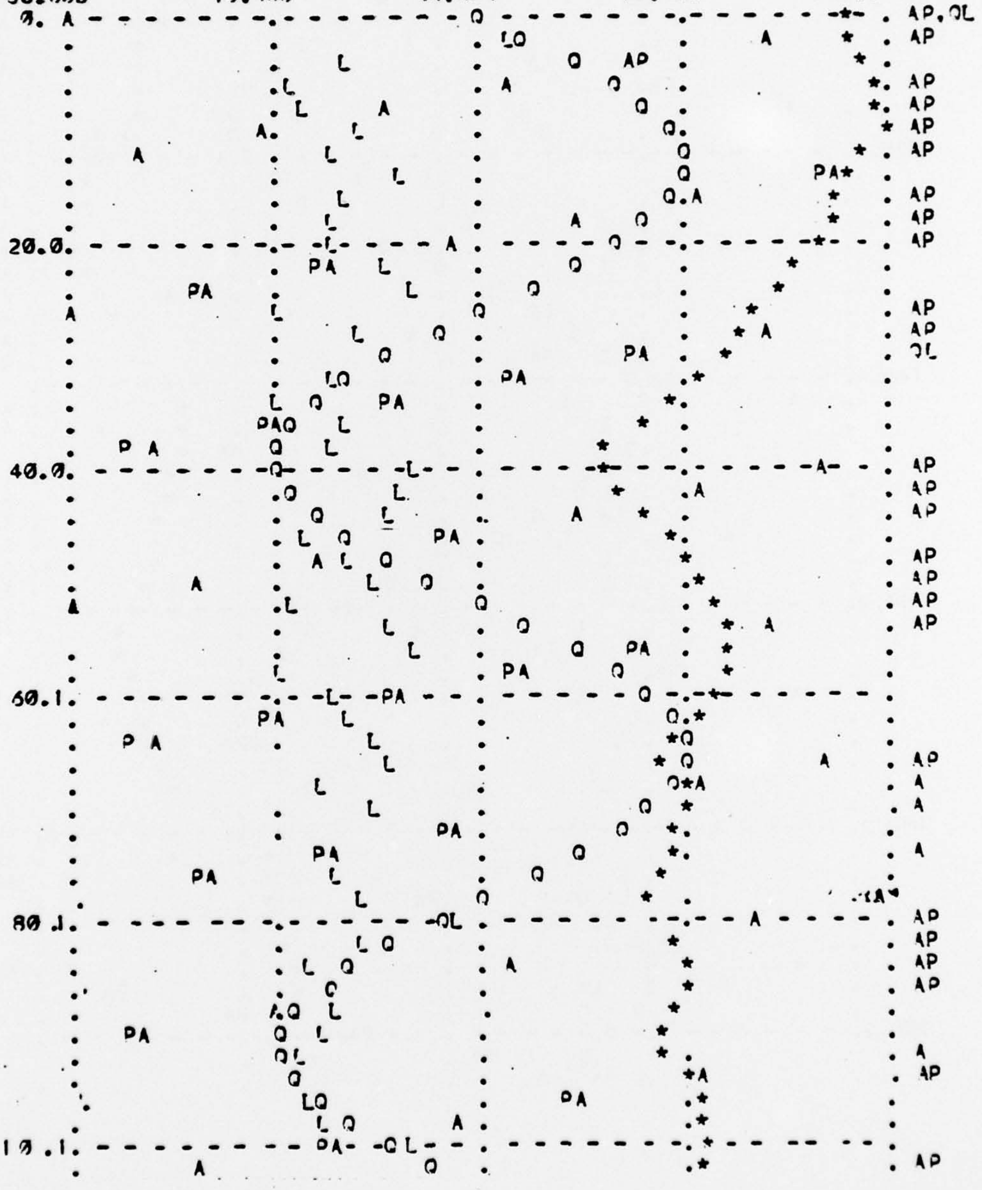
```
      .                  L.      Q        PA  .                   .*                  .
 100.1. - - - - - -L- - - . - A - - Q - - - - . - - - - - - - - - . * - - - - - - - - . AP
      .           A      L.             Q     .                   . *                 . AP
      .            L      .                   Q                   . *                AP
      .                   . L                 .    Q              .      A            . AP*
      .               L   .                   .        Q     A    .       *           . AP
      .                L  .                   .  A         Q      .         *         . AP
      .            L      .          A        .               Q   .         *         . AP
      .                 PA.                   .                  Q.         *         . AL
      .    PA          L  .                   .                   Q         *         .
      .                   . L                 .                   Q          * A       . AP
 120.1. - - - - - - - - - . - - - - L - - - - . - - - - - - - - -Q.A- - - - - -*- - - . AP
      .                   .   L               .       A       Q   .             *     . AP
      .                  L.               A   .            Q      .               *   . AP
      .                  L.   A               .        Q          .               *   . AP
      .           A L     .                   .    Q              .              *    . AP
      .                L  .                   Q                   .            *     A. AP
      .              L    .             Q     .                   .      A    *        . AP
      .                L  .         Q         .              A    .          *        . AP
      .                L  .     Q             .  A                .        *          . AP
      .                  L.   Q    PA         .                   .      *            .
 140.1. - - - - - - - L-PA.Q- - - - - - - - - . - - - - - - - - - . - -*- - - - - - - .
      .    A            L Q                   .                   .   *               . AP
      .                 L Q                   .                   .  *         A      . AP
      .                  L.Q                  .                   PA *                .
      .               L   .   Q               .       A           .    *              . AP
      .                  L.     Q         A   .                   .    *              . AP
      .              L    .   A      Q        .                   .    *              . AP
      .           A      L.             Q     .                   .      *            . AP
      .               L   .                   Q                   .      *           A. AP
      .               L   .                   .    Q              .      A*           . AP
 160.2. - - - - - -L- - - . - - - - - - - - - . - - - -Q- -A- - - . - - - -*- - - - - . AP
      .                  L.                   .  A         Q      .        *          . AP
      .                L  .        PA         .               Q   .        *          .
      .                 PA.                   .                  Q.        *          . AL
      .    PA         L   .                   .                   Q       *           .
      .               L   .                   .                   Q       *    A      . AP
      .              L    .                   .                  QPA      *           .
      .                   .L                  .       PA      Q   .       *           .
      .               L   .               A   .            Q      .    *              . AP
      .                L  .   A               .        Q          .   *               . AP
 180.2. - - -  PA-   L   -. - - - - - - - - - . -  Q - - - - - - -.* - - - - - - - -  .
      .                L  .                   Q                *  .                  A. AP
      .              L    .             Q     .                  *.     A             . AP
      .                   L          Q        .              A   *.                   . AP
      .               L   .     Q             .PA              *  .                   .
      .               L   .   Q    PA         .               *   .                   .
      .               L PA.Q                  .               *   .                   .
      .    PA           L Q                   .             *     .                   .
      .               L   Q                   .            *      .           PA      .
      .                  L.Q                  .              *    PA                  .
 200.2. - - - - - - - L - .-  Q - - - - - - - . - -  PA- -  -*- - . - - - - - - - - - .
      .                L  .     Q         PA  .              *    .                   .
      .               L   .   PA    Q         .            *      .                   .
      .         PA     L  .               Q   .           *       .                   .
1PAGE    2  MISSION CAPABILITY MODEL
```

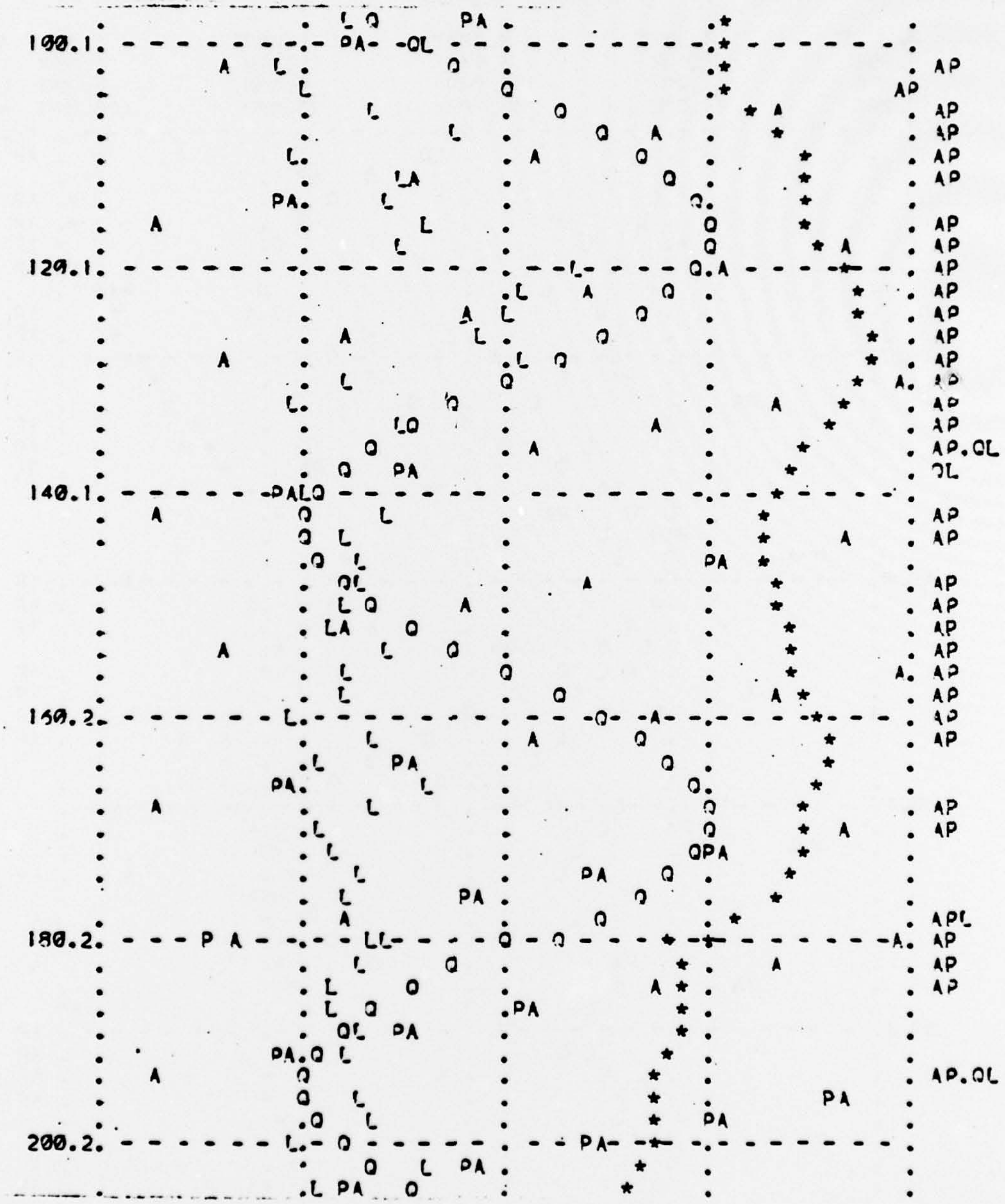
APPENDIX F

RATE OF REPAIR SIMULATION

```
1PAGE   1   MISSION CAPABILITY MODEL
   AVHR=A  PRHR=P  SQP=Q  LOSC=L  MISCP=*

   0.     T            0.350T            0.700T            1.050T            1.400T AP
   0.850               0.900             0.950             1.000             1.050  Q
   2.000               3.000             4.000             5.000             6.000  L
  60.000              70.000            80.000            90.000           100.000  *
```




100.1
120.1
140.1
160.2
180.2
200.2
AP
AP.QL
QL
APL

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